Recent results on charmonium production in Pb-Pb collisions with nuclear overlap in ALICE

Robin Caron, on behalf of the ALICE collaboration

Institut de Physique des Deux Infinis (CNRS-IN2P3)

March 30, 2023

Outline

- Introduction
- Charmonium production in Pb-Pb collisions
  - Inclusive J/ψ and $\psi(2S)$ production
  - Prompt and non-prompt J/ψ production
  - Coherent J/ψ photoproduction in collisions with nuclear overlap
- Summary

Evolution of a heavy-ion collision

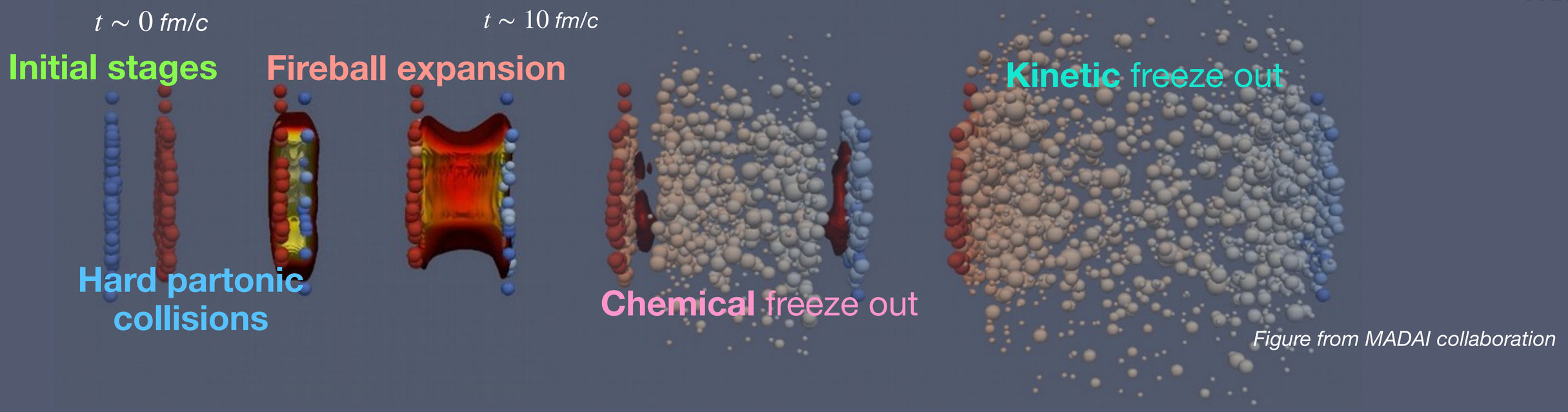
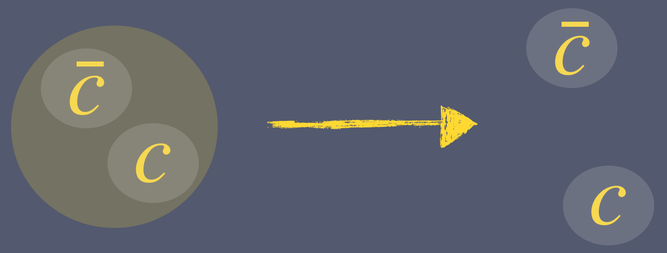


Figure from MADAI collaboration

Charmonium: a powerful tool to study **medium properties and initial conditions**

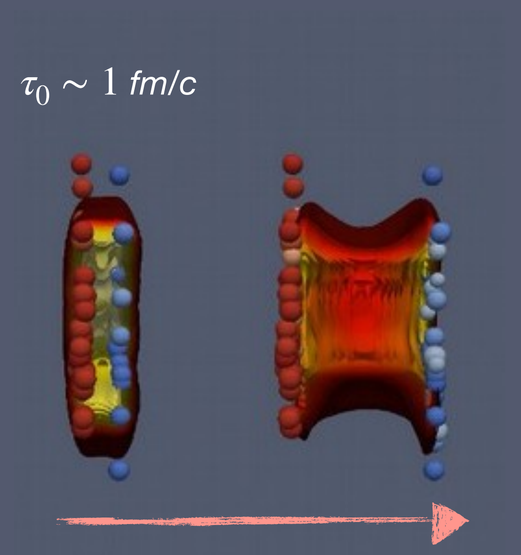


Signature of deconfinement:

suppression of charmonia inside the quark-gluon plasma (QGP), originally proposed in [1]

[1] T. Matsui, *H. Satz, Phys.Lett.B 178 (1986) 416-422*

Why charmonium?

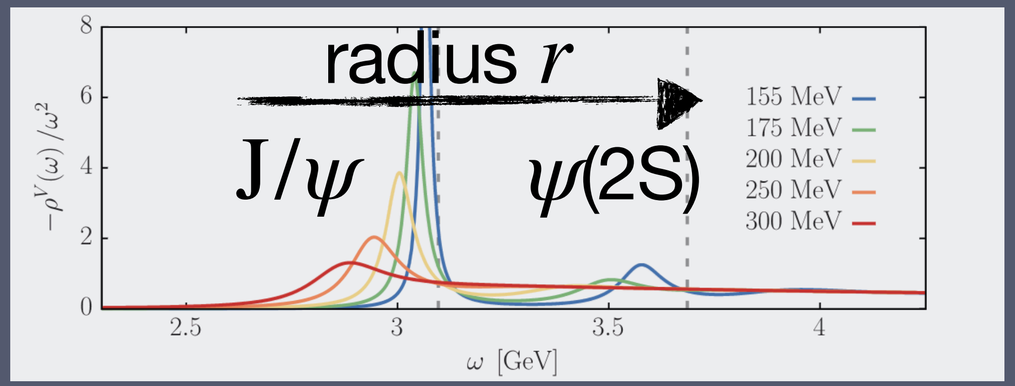


deconfined medium
QGP

color screening and medium-induced dissociation (with static vs dynamic dissociation)

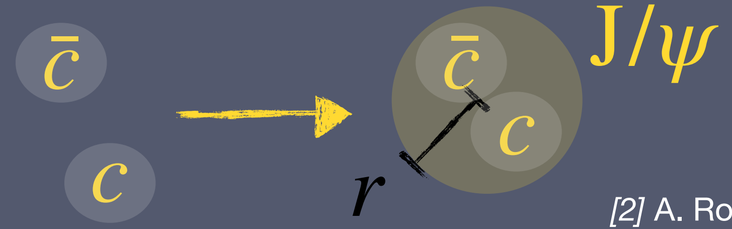
excited states more suppressed w.r.t. ground state

sensitive to **medium temperature**



[2]

In central Pb-Pb collision at LHC: $O(100)$ $c\bar{c}$ pairs produced close to $\tau \sim$ 0.1 fm/c (and few $b\bar{b}$)

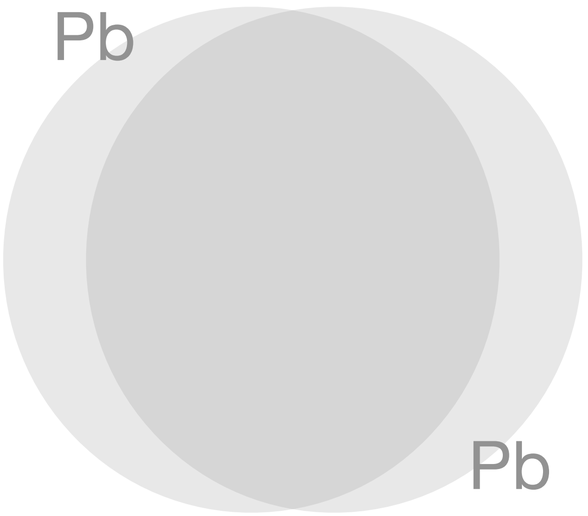


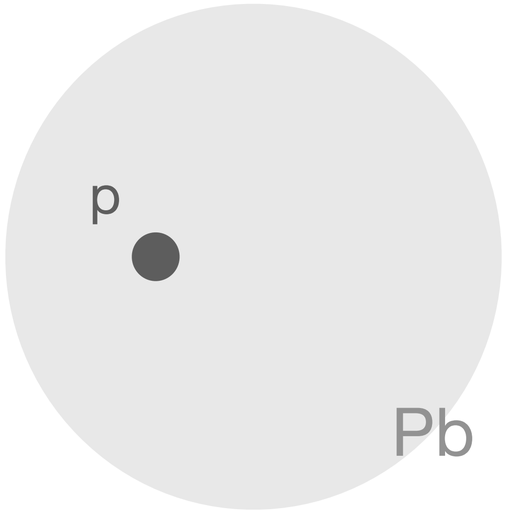
Regeneration: strongly supported scenario at LHC due to large $N_{c\bar{c}}$ created - affecting differently J/ψ and ψ(2S)

[3,4]

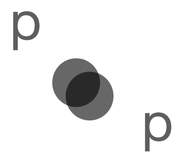
[2] A. Rothkopf, Phys. Rep. 858*(2020) 1-117*
[3] *Braun-Munzinger, Stachel, Nature 448 (2007) 302*
[4] R.L. Thews et al., Phys. Rev. C 63 (Apr. 2001) 054905

Charmonium production across systems size





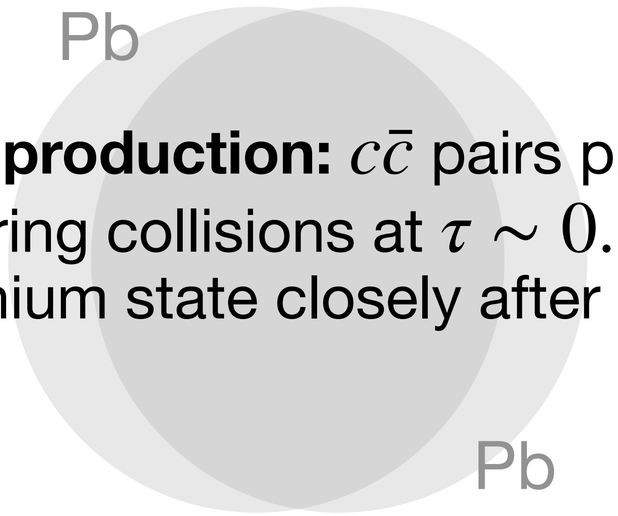
cold nuclear matter effects



reference system
test of QCD

high multiplicity p-Pb or pp: study of **multiparton interactions** and **collectivity in small system**

Charmonium production across systems size



Hadronic production: $c\bar{c}$ pairs produced by hard scattering collisions at $\tau \sim 0.1$ and bound charmonium state closely after (< 1 fm/c)

$$gg \rightarrow c\bar{c}$$

Mainly **gluon initiated process at LHC** (might be also $q\bar{q}$ annihilation)

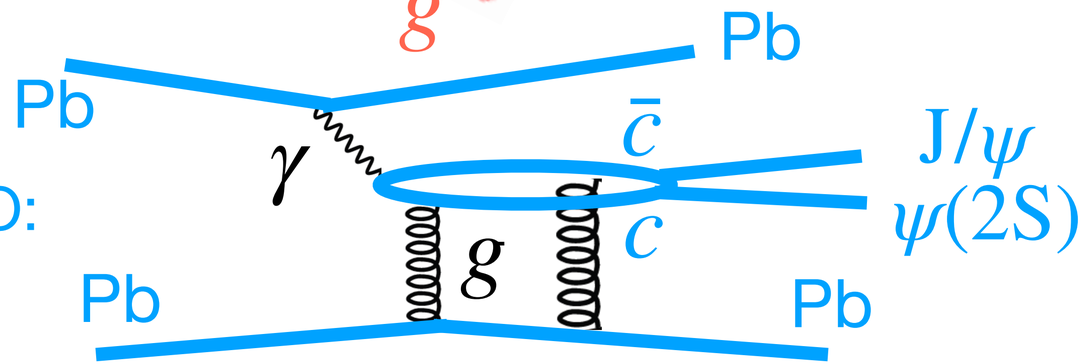
$$\mathrm{J}/\psi + g \rightarrow c + \bar{c} + g \quad \text{if } T > T_{\mathrm{diss}}$$

$$c + \bar{c} \rightarrow \mathrm{J}/\psi + g \quad \text{if } T < T_{\mathrm{diss}}$$

Hot medium effect: $c\bar{c}$ dissociation vs recombination, collectivity, heavy quark energy loss

Photoproduction: first studied in Ultra Peripheral Collisions (UPCs), now also observed in Pb-Pb with nuclear overlap, probe the initial stages of the collision and possibly new QGP probe

LO:



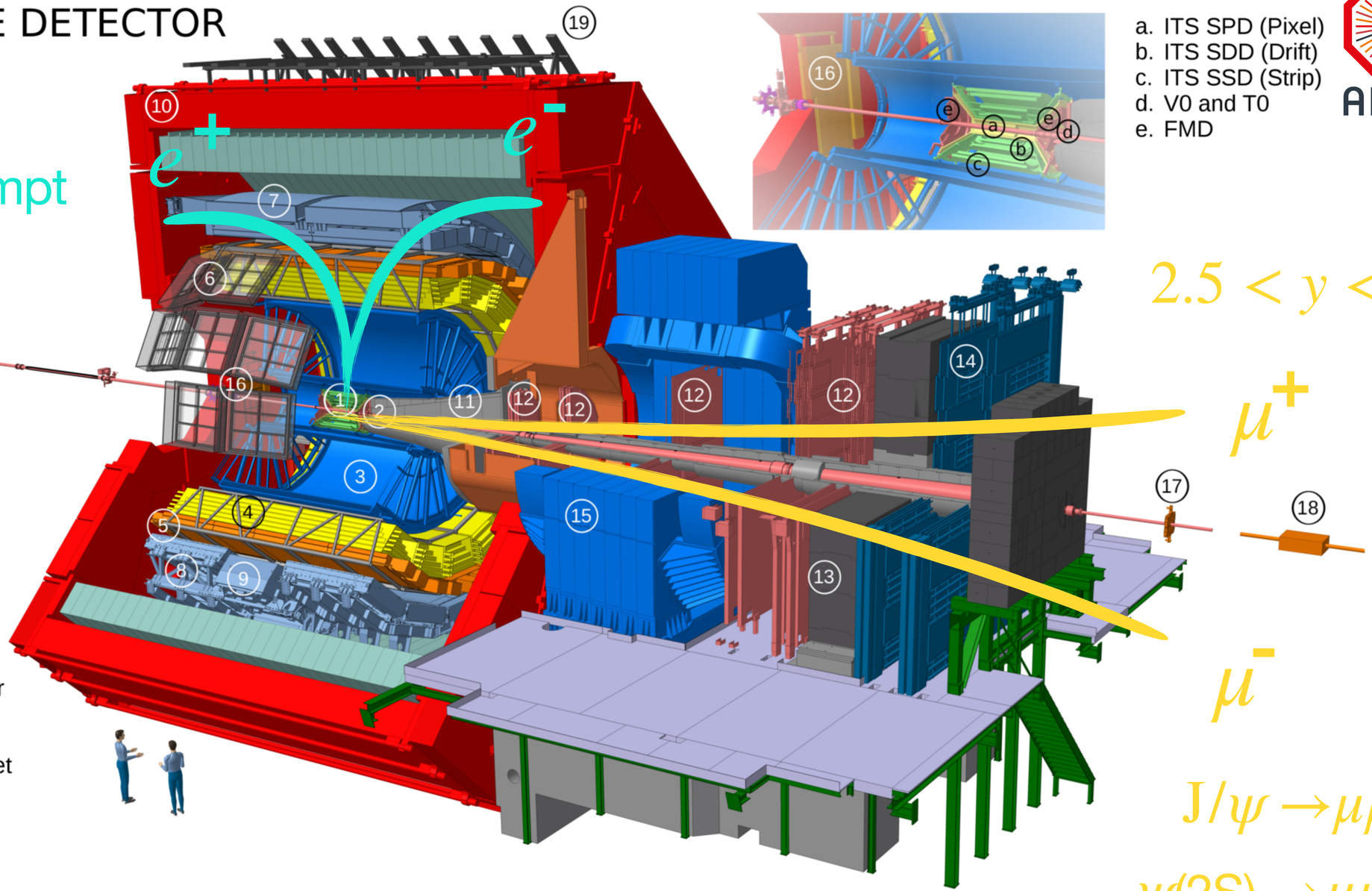
THE ALICE DETECTOR

$J/\psi \rightarrow ee$

$|y| < 0.9$

Prompt/Non-prompt separation

Run 2 configuration



$2.5 < y < 4$

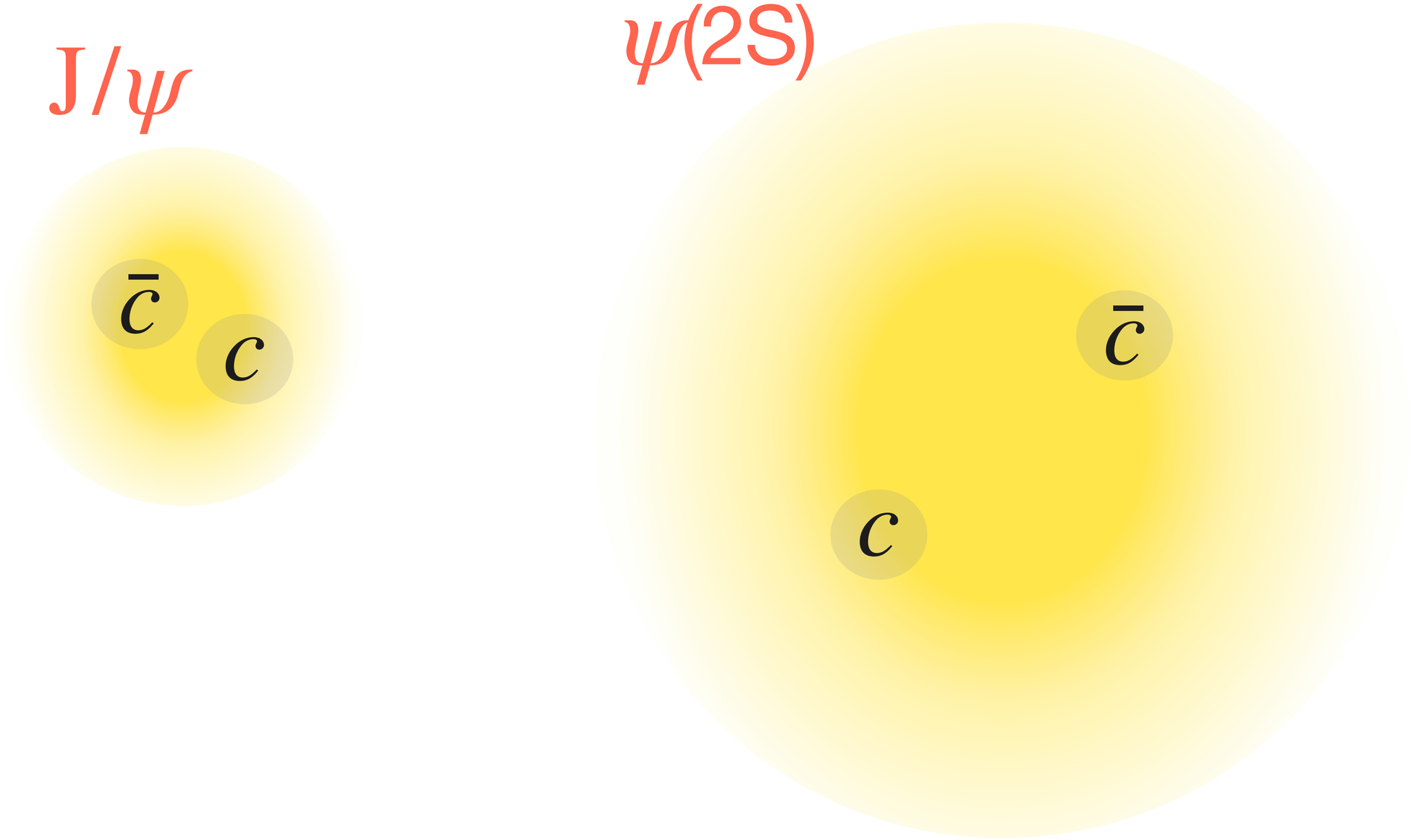
μ^+

μ^-

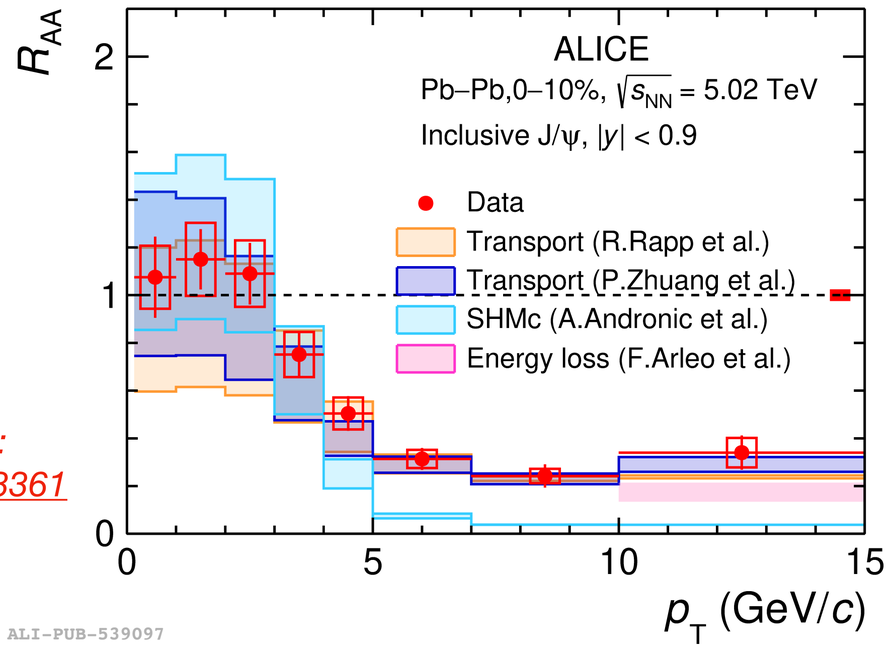
$J/\psi \rightarrow \mu\mu$

$\psi(2S) \rightarrow \mu\mu$

Inclusive measurement down to p_T = 0 GeV/c for both y


J/ψ
c̄
c
ψ(2S)
c̄
c

J/ψ nuclear modification factor (R_{AA})



NEW PAPER:
arXiv:2303.13361

- Measuring production in AA relative to production in pp collisions:
  - > 1: Enhancement
  - < 1: Suppression

$$R_{AA} = \frac{1}{\langle T_{AA} \rangle} \frac{d^2N_{AA}/dp_T dy}{d^2\sigma_{pp}/dp_T dy}$$

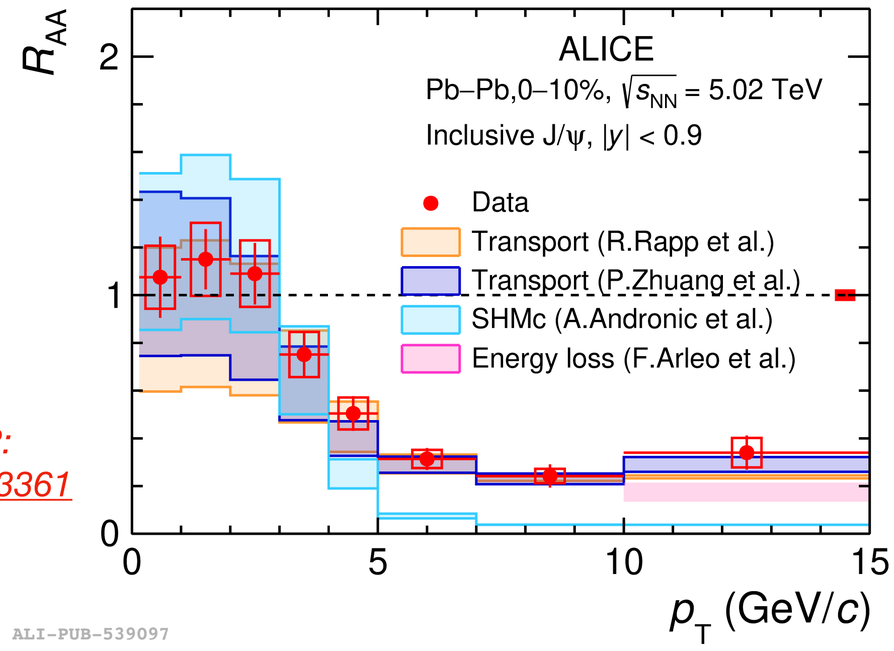
*$\langle T_{AA} \rangle$: average nuclear overlap function

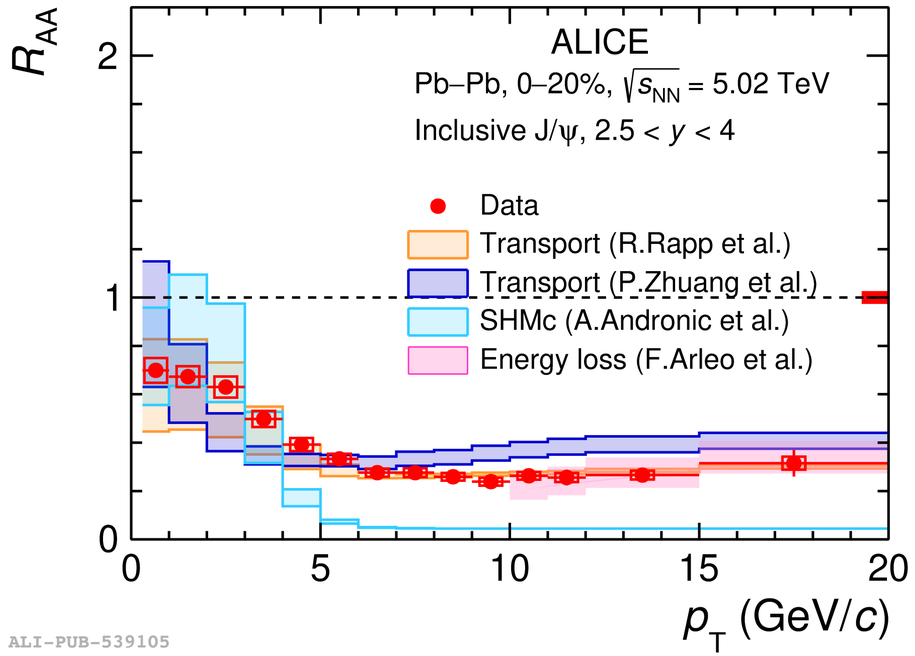
- Models implementing **regeneration**, either at the freeze-out (SHMc) or during the medium evolution (TAMU), are in agreement with data at low p_T
- J/ψ R_{AA}: more suppressed at high p_T and showing a rising trend towards lower p_T

SHMc: Andronic A. et al., Phys. Lett. B797 (2019) 134836 EnergyLoss: F. Arleo Phys. Rev. Lett. 119, 062302 (2017)
TAMU: Rapp R. Et al. Nucl.Phys.A 943 (2015) 147-158 Transport: P. Zhuang et al. Phys.Rev.C89,054911(2014)

J/ψ nuclear modification factor (R_{AA})

NEW PAPER:
arXiv:2303.13361



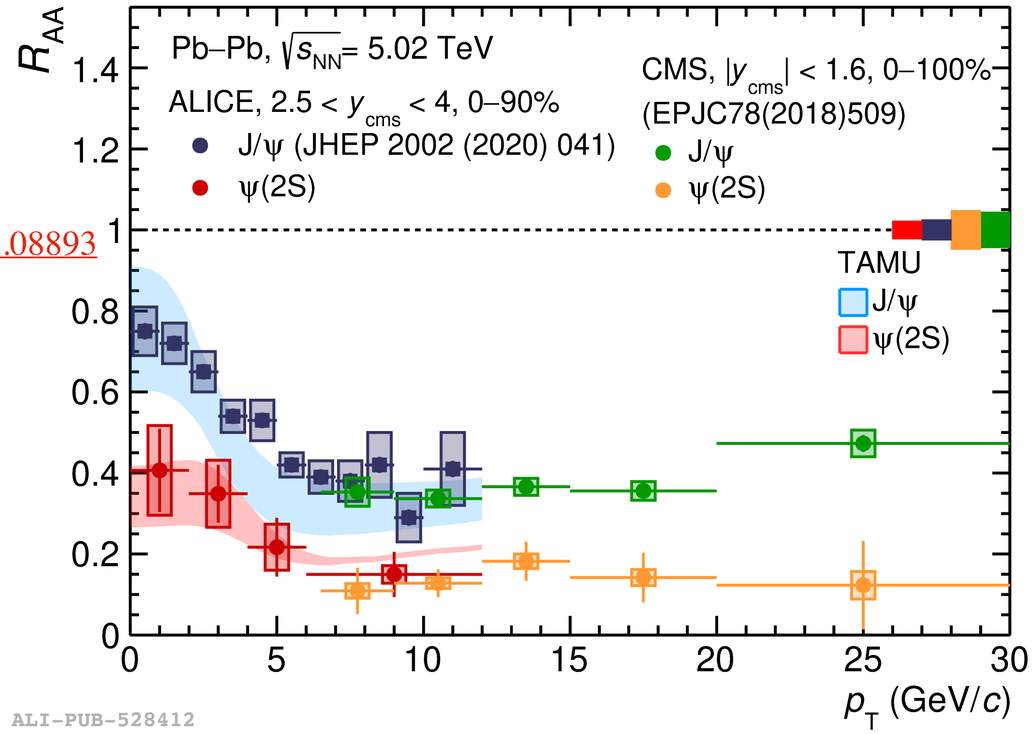


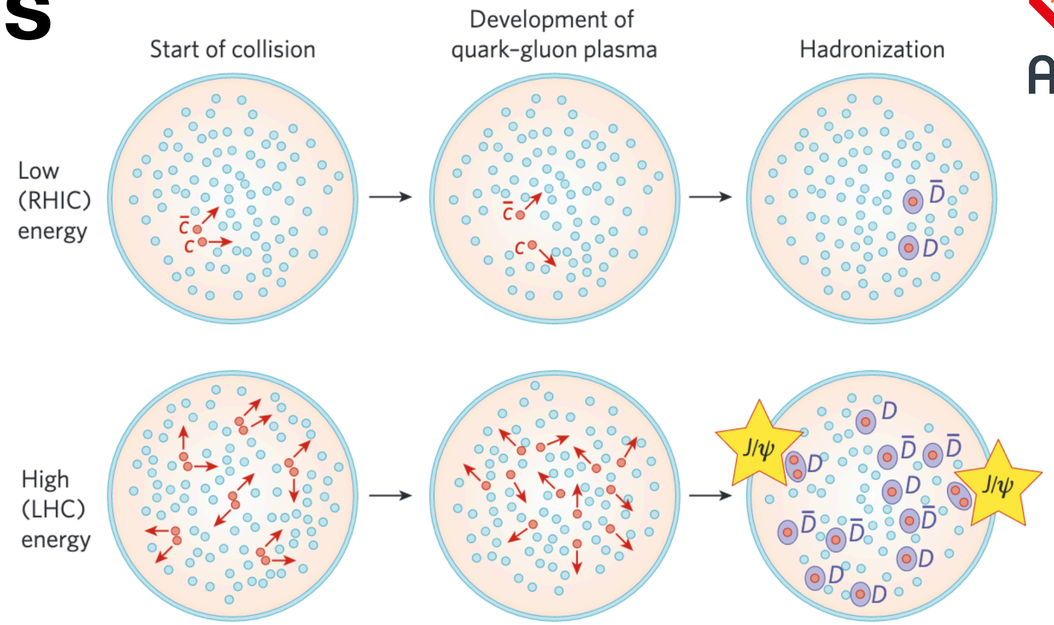
- Models implementing **regeneration**, either at the freeze-out (SHM) or during the medium evolution (TAMU), are in agreement with data at low p_T
- J/ψ R_{AA}: more suppressed at high p_T and showing a rising trend towards lower p_T
- $R_{AA}^{mid-y} > R_{AA}^{fwd-y}$ (low p_T) as expected by recombination scenario ($N_{c\bar{c}}^{mid-y} > N_{c\bar{c}}^{fwd-y}$)

SHMc: Andronic A. et al., Phys. Lett. B797 (2019) 134836 EnergyLoss: F. Arleo Phys. Rev. Lett. 119, 062302 (2017)
TAMU: Rapp R. Et al. Nucl.Phys.A 943 (2015) 147-158 Transport: P. Zhuang et al. Phys.Rev.C89,054911(2014)

$\psi(2S)$ R_{AA} in Pb-Pb collisions

arXiv:2210.08893





P. Braun-Munzinger, J. Stachel., Nature 448, 302–309 (2007)

- At low-p_T: **recombination** expected to play an important role for both J/ψ and $\psi(2S)$

- J/ψ and $\psi(2S)$ **suppression hierarchy** over the full p_T range and for centrality integrated

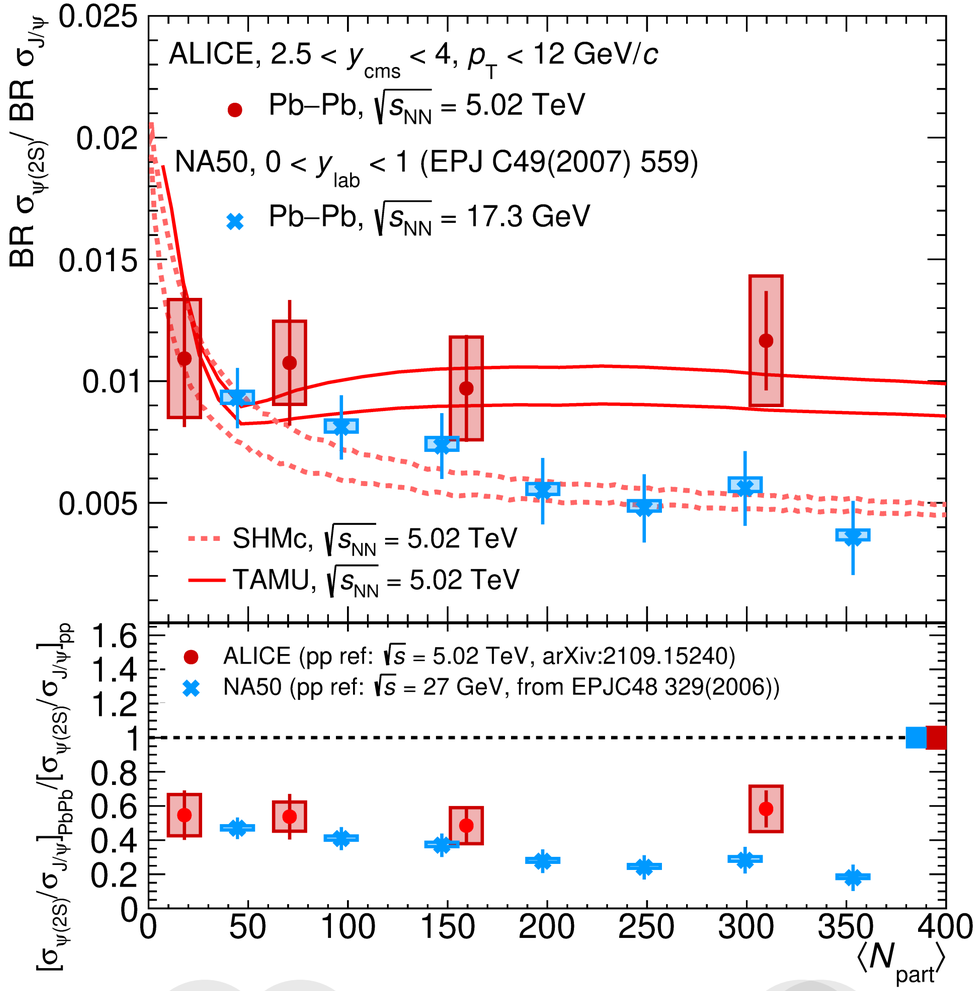
- At high p_T: agreement with CMS data ($|y_{cms}|$ < 1.6) where **energy loss** calculations provide a good description here for the J/ψ (see figures in previous slides)

TAMU: Du X. and Rapp R., Nucl.Phys.A 943 (2015) 147-158

$\psi(2S)$ / J/ψ ratio in Pb-Pb collisions

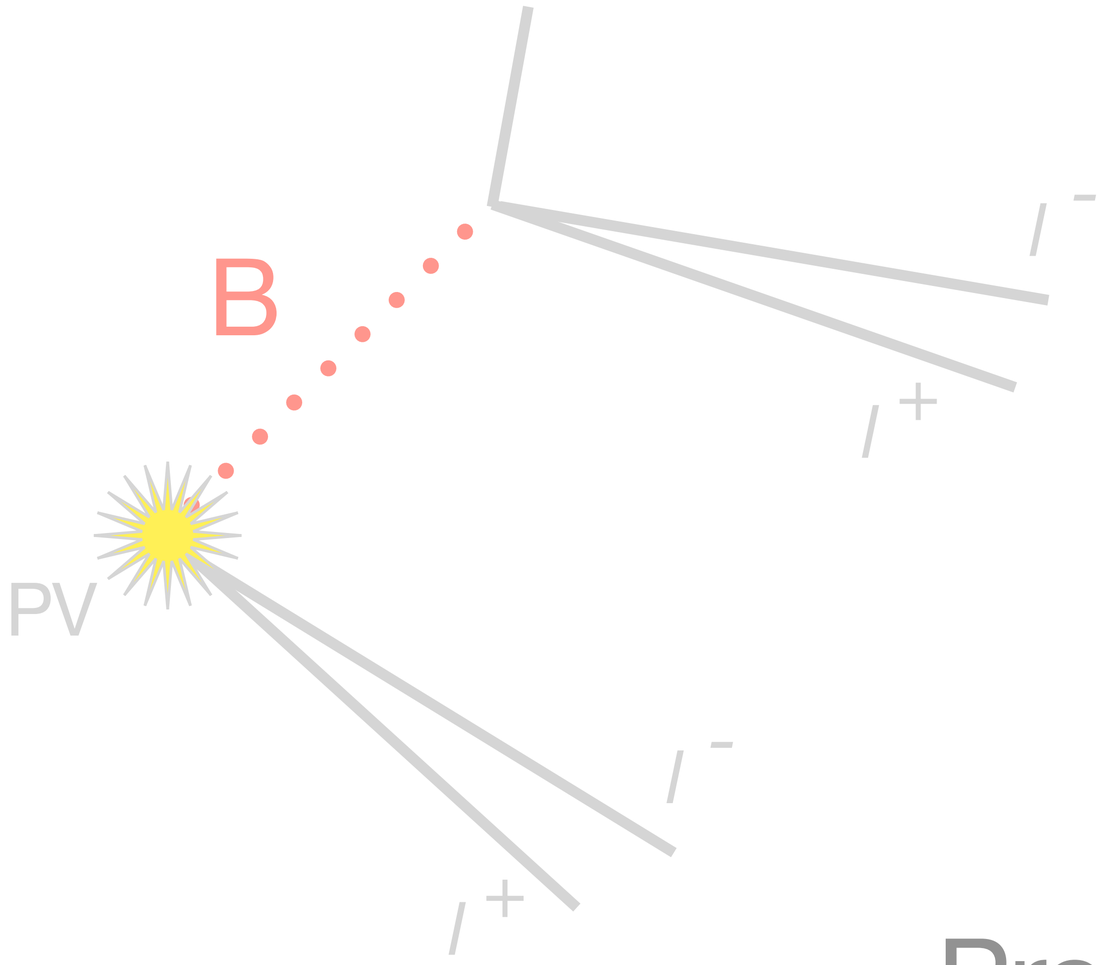
arXiv:2210.08893

- **Hint of a larger** $\psi(2S)$ / J/ψ ratio in central collisions at the LHC w.r.t SPS (ratio described by TAMU model, while it is underestimated by SHMc in central events)
- No evidence of centrality dependence
- Strong suppression of the $\psi(2S)$ / J/ψ ratio in PbPb w.r.t pp



ALI-PUB-528400

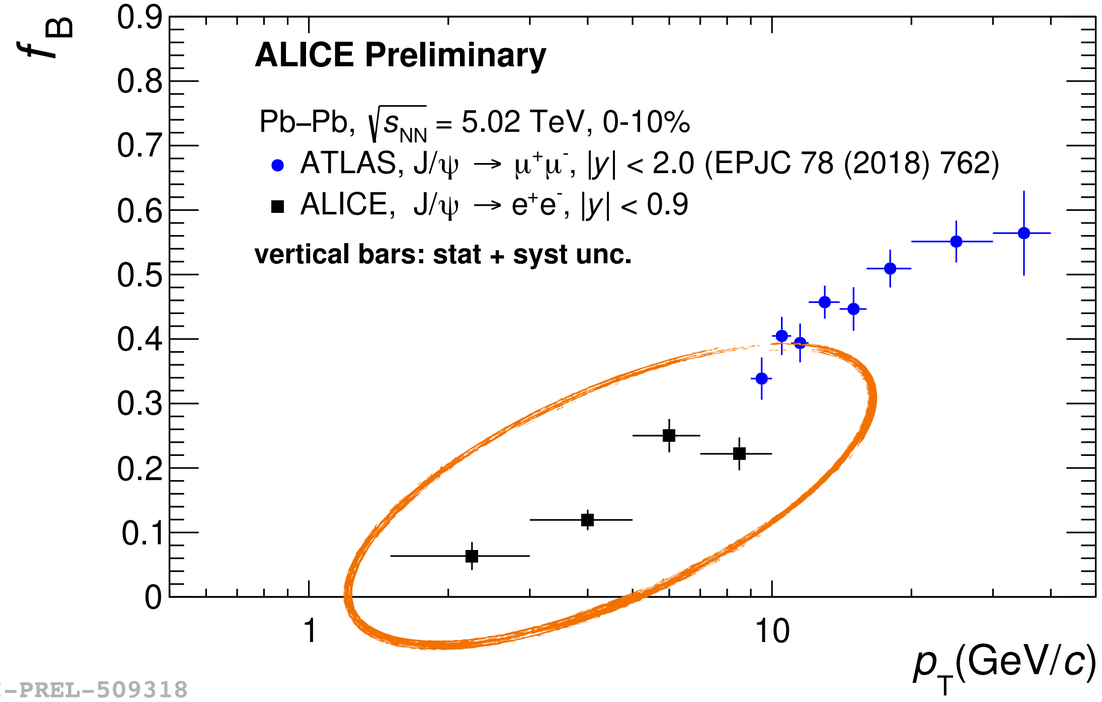
TAMU: Du X. and Rapp R., Nucl.Phys.A 943 (2015) 147-158
SHMc: Andronic A. et al., Nature 561, 321–330 (2018)

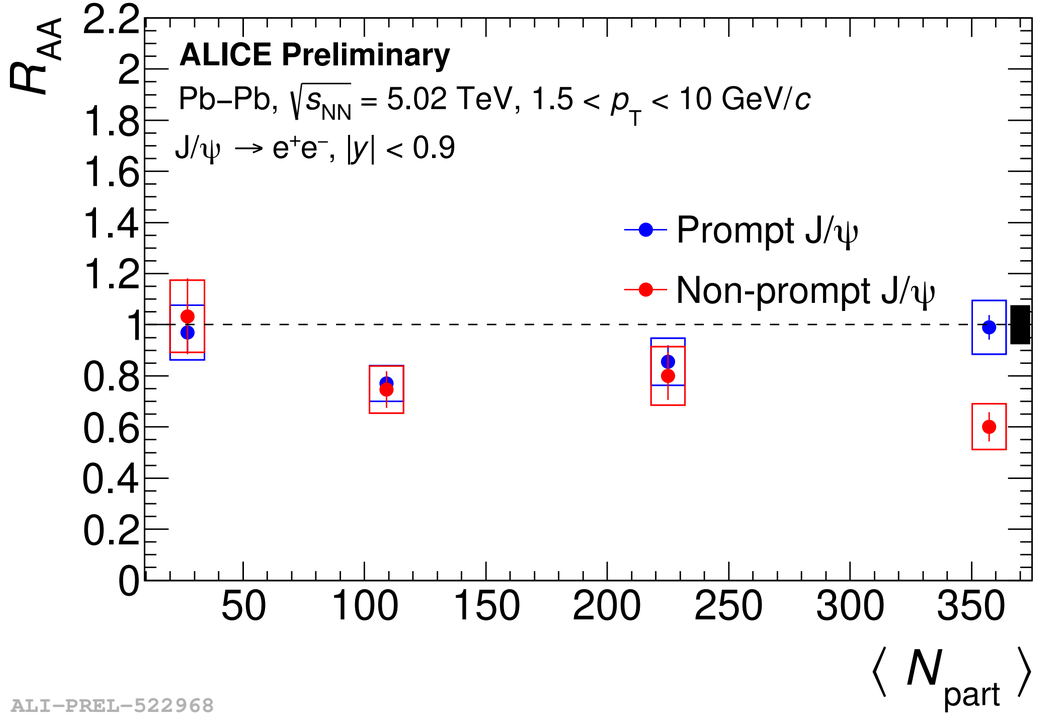


Non-prompt J/ψ

Prompt J/ψ

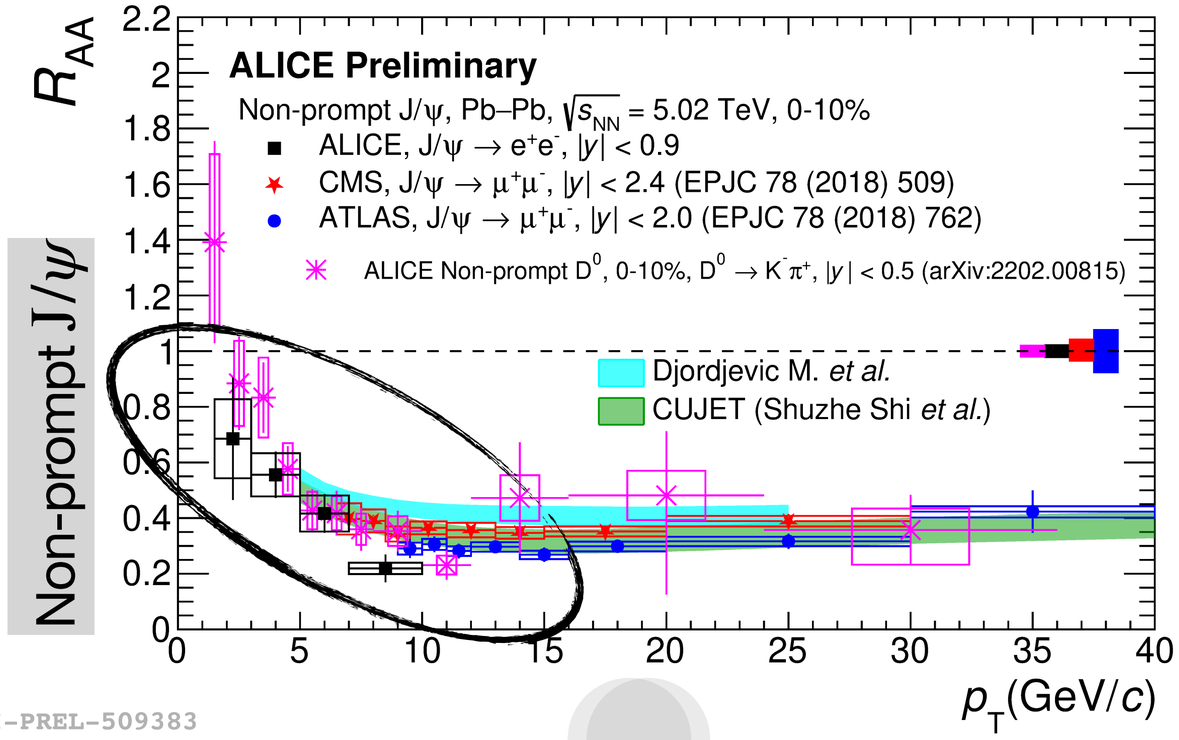
Prompt/non-prompt J/ψ production in Pb-Pb collisions

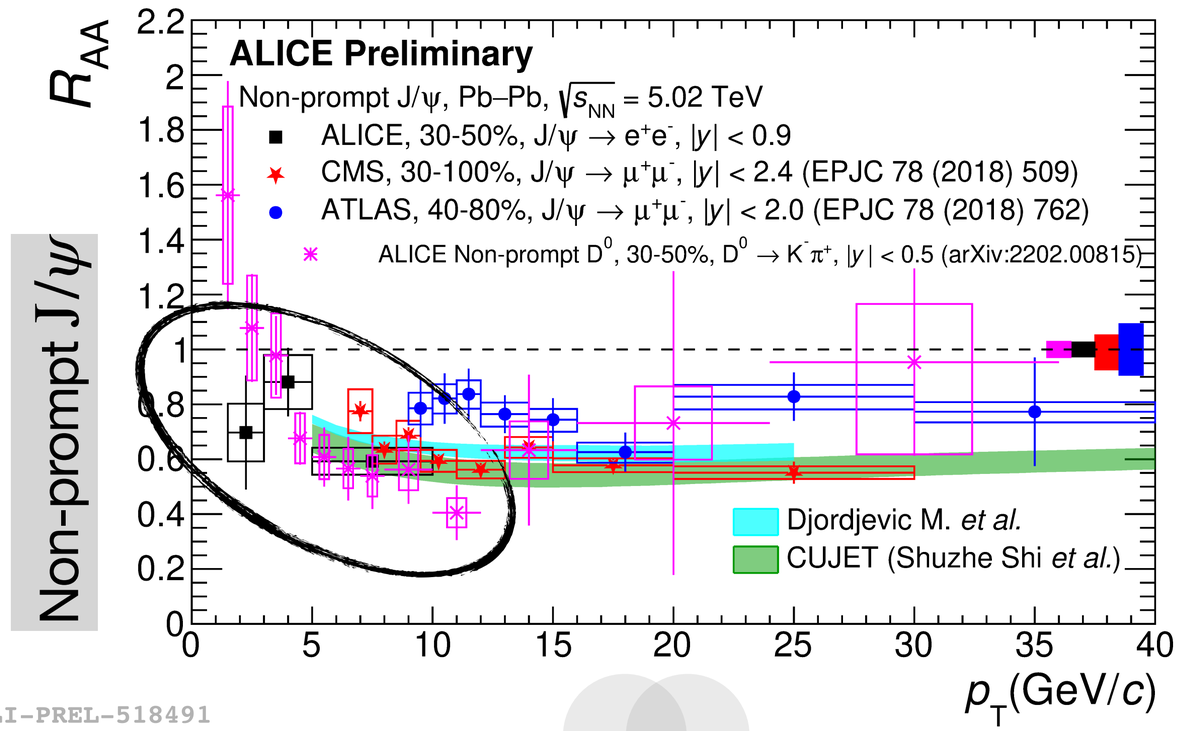




- ALICE extends non-prompt J/ψ fraction (f_B) measurements down to very low p_T
- Non-prompt J/ψ **more suppressed towards more central collisions**
- **Recombination** can explain the rising trend of $R_{AA}^{\text{prompt } J/\psi}$ towards more central collisions

Measuring beauty from non-prompt J/ψ in Pb-Pb





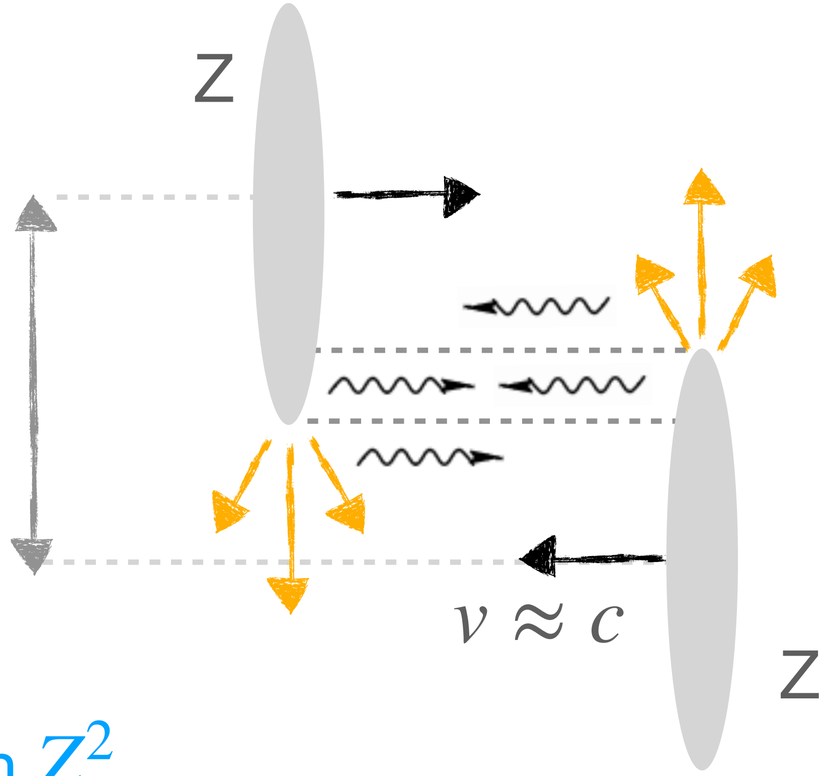
- Measurements of non-prompt J/ψ and non prompt D^0 mesons give access to b-hadron suppression at low p_T
- Models including **collisional and radiative energy loss** consistent with data (high p_T)

CUJET: Shuzhe S. et al. Chin.Phys.C 43 (2019) 4, 044101, Chin.Phys.C 42 (2018) 10, 104104
Djordjevic M. et al. Front. Phys. 10:957019 (2022)

Photo-producted J/ψ

UPC:
$b > R_1 + R_2$

$b < R_1 + R_2$

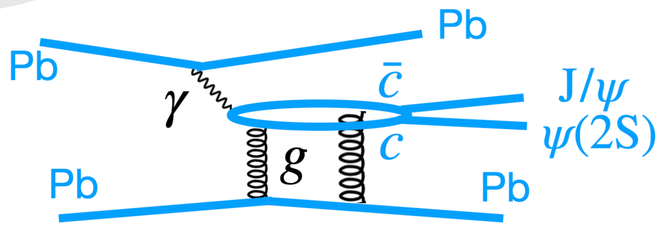


Peripheral Pb-Pb

Small $\langle N_{\mathrm{part}} \rangle$

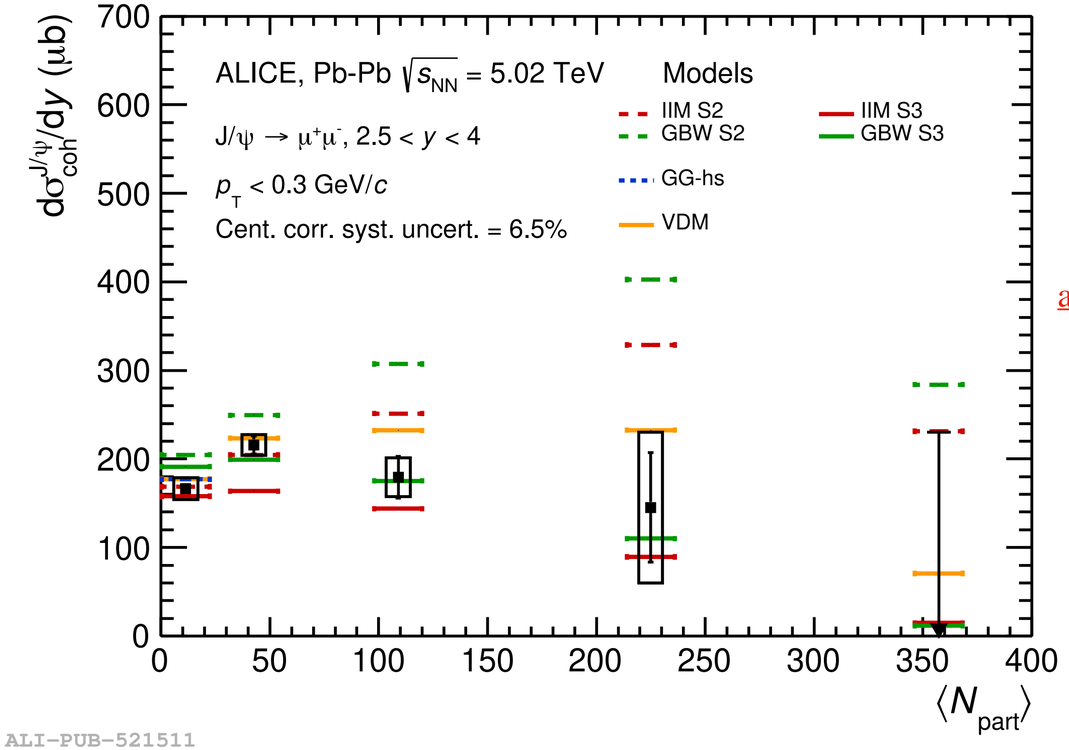
γ flux grows with Z^2

EM field carried by ultrarelativistic Pb nuclei

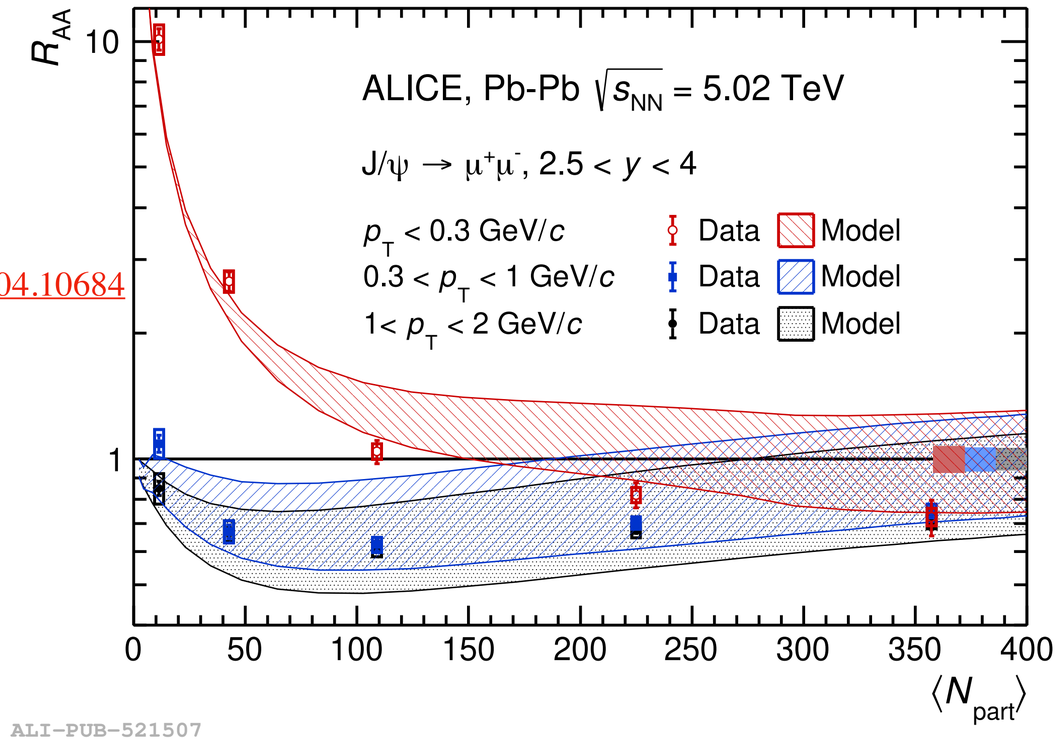


(Coherently) photo-producted J/ψ present in Pb-Pb collisions with nuclear overlap, with characteristic production peak at $p_{\mathrm{T}} \sim 60$ MeV/c

J/ψ photoproduction in Pb-Pb at forward rapidity



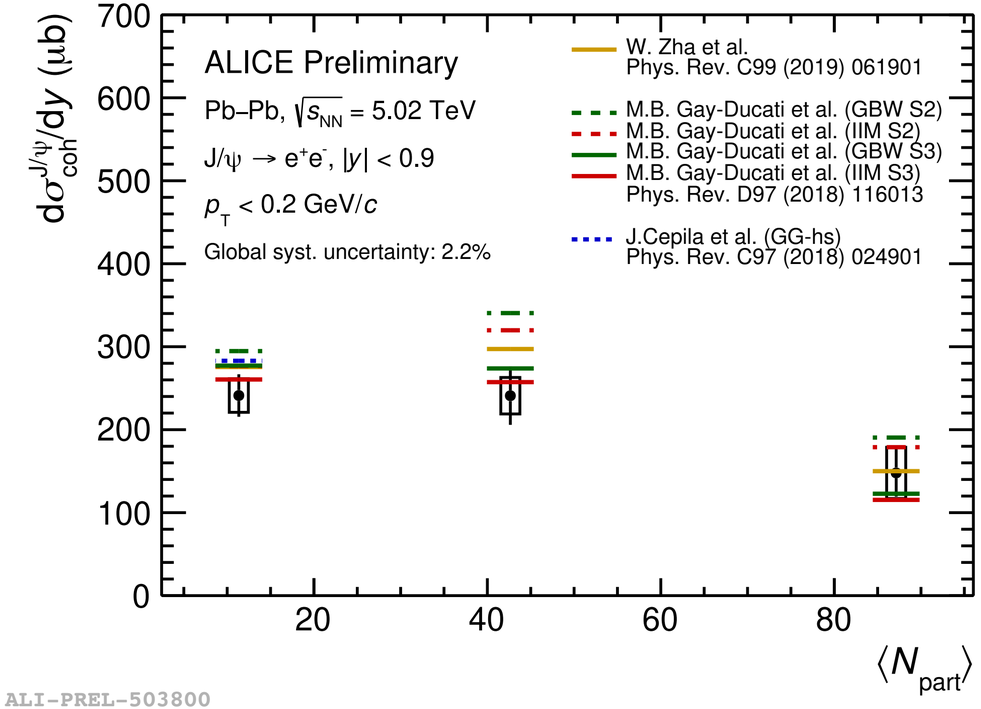
arXiv:2204.10684

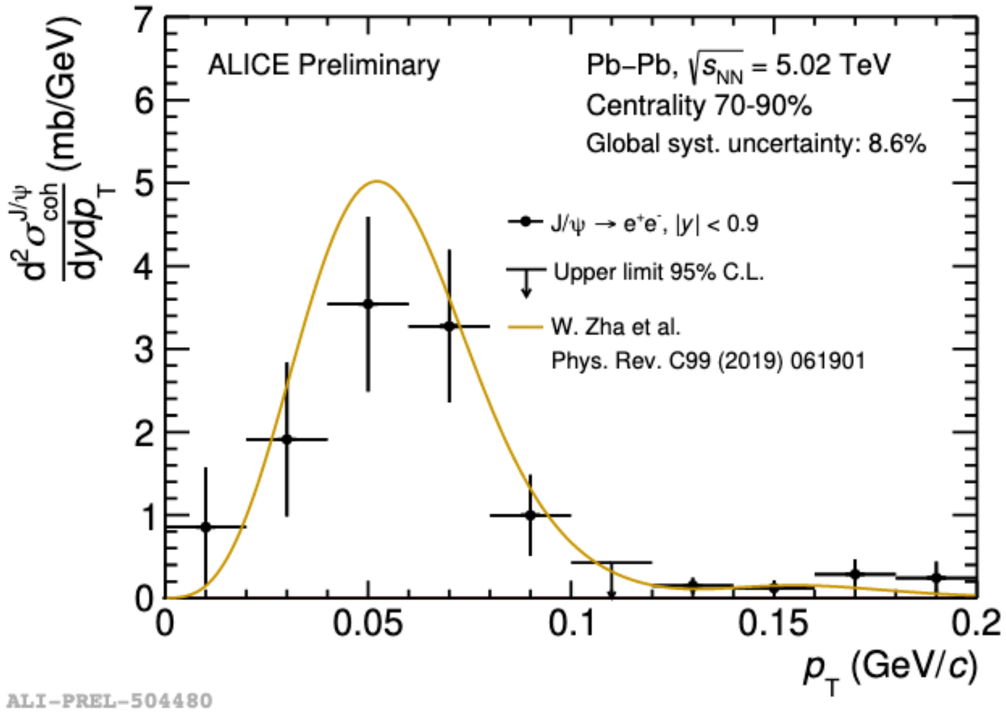


- Clear **observation** of J/ψ excess at very low p_T , **photoproduction not only in UPCs**
- EM fields are producing abundantly J/ψ for p_T < 0.3 GeV/c. Data are compatible with the "S3" scenario || (where the overlap region is assumed to not contribute to σ_{coh}) and with VDM (modification of the photon γ flux only)

VDM: M. Klusek-Gawenda et al. Phys. Rev. C 93, 044912 (2016) Model: W. Shi et al., Phys.Lett. B777 (2018) 399-405
GG-hs: J. Cepila et al. Phys. Rev. C 97, 024901 (2018) IIM, GBW: M.B. Gay Ducati et al. Phys. Rev. D 97, 116013 (2018)

J/ψ photoproduction in Pb-Pb at midrapidity

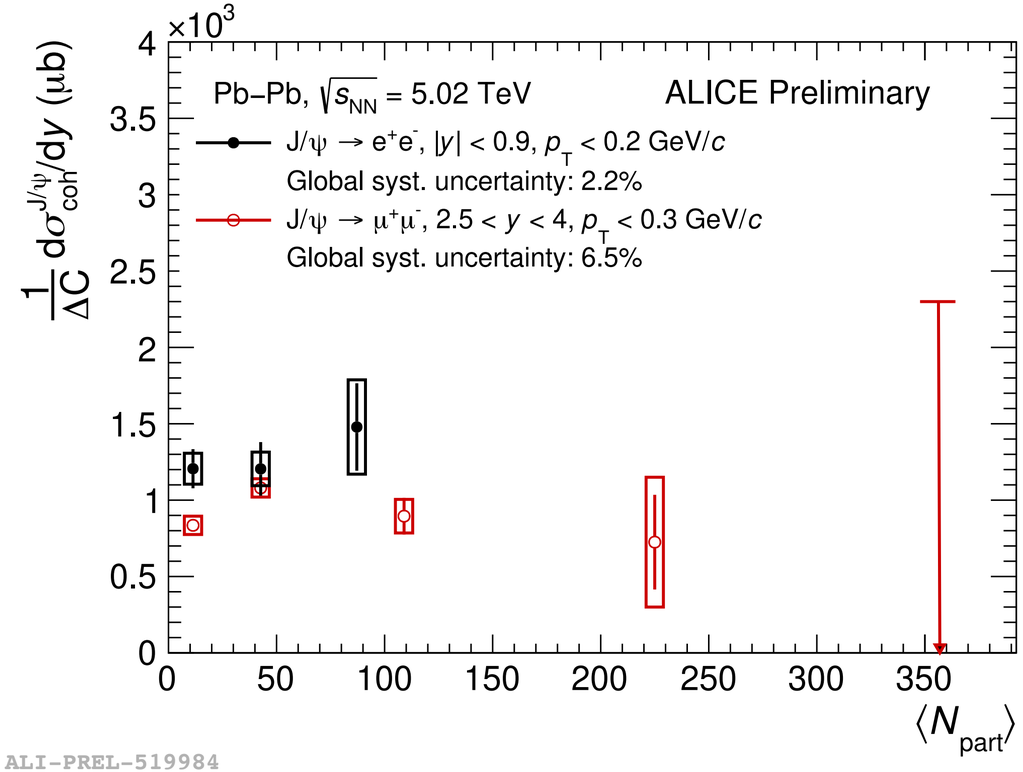


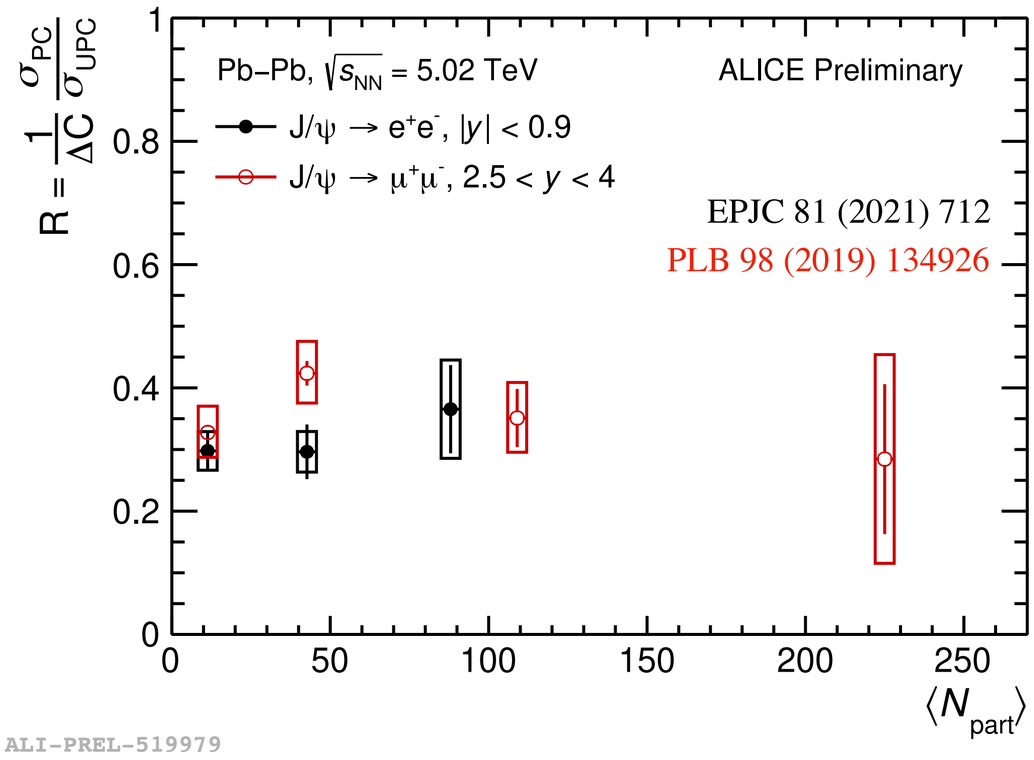


- Clear **excess** observed in the J/ψ production in peripheral Pb-Pb at mid-y (p_T < 0.2 GeV/c)
- Models including at least γ flux (+ possibly $\sigma_{\gamma Pb}$) modification can explain the data for both y
- In addition model (W. Zha et al.) adding **destructive interferences** can describe the p_T dependence of $d^2\sigma/dp_T dy$

W. Zha et al., PRC 99 (2019) 6, 061901 IIM, GBW: M.B. Gay Ducati et al. Phys. Rev. D 97, 116013 (2018)

Coherent J/ψ production with nuclear overlap, normalized to UPC

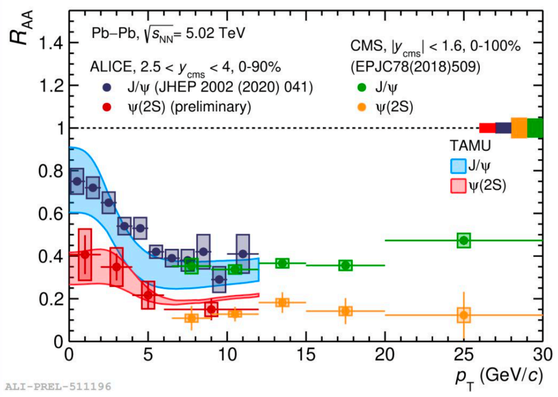


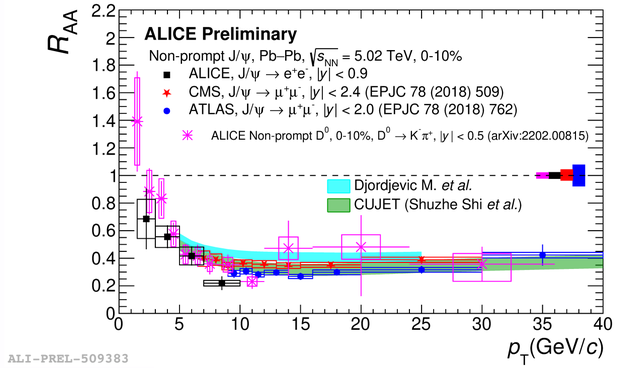


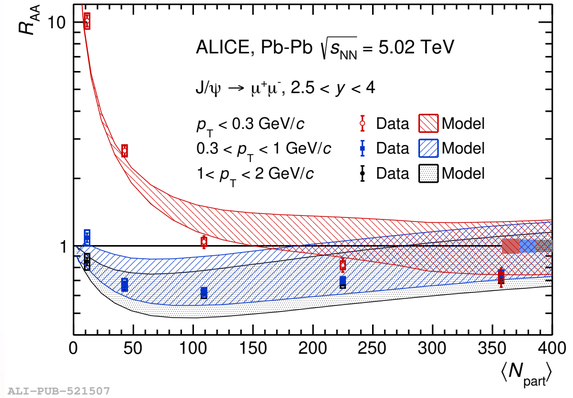
- No clear evidence of centrality dependence of the coherent J/ψ cross-section at mid and forward rapidity, also the case for the ratio: $R = \frac{1}{\Delta C}\frac{\sigma_{PC}}{\sigma_{UPC}}$

Summary

- **Sequential suppression** well studied for bottomonia but now also observed for charmonia, hint of low-p_{T} $\psi(2S)$ recombination
- Prompt J/ψ less suppressed towards more central collisions (charm quark recombination)
- Non-prompt J/ψ high p_{T} data could be explained by models including **collisional and radiative energy loss**
- **Observation** of coherent J/ψ photoproduction in different y regions not only in UPC but also in peripheral Pb-Pb collisions, where EM fields are competing with the strong interactions

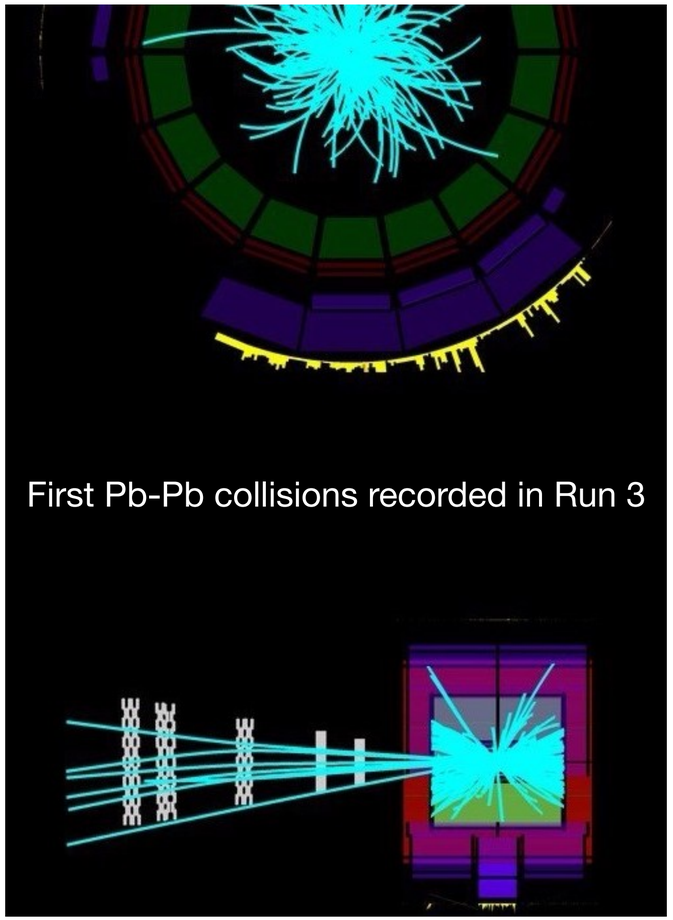






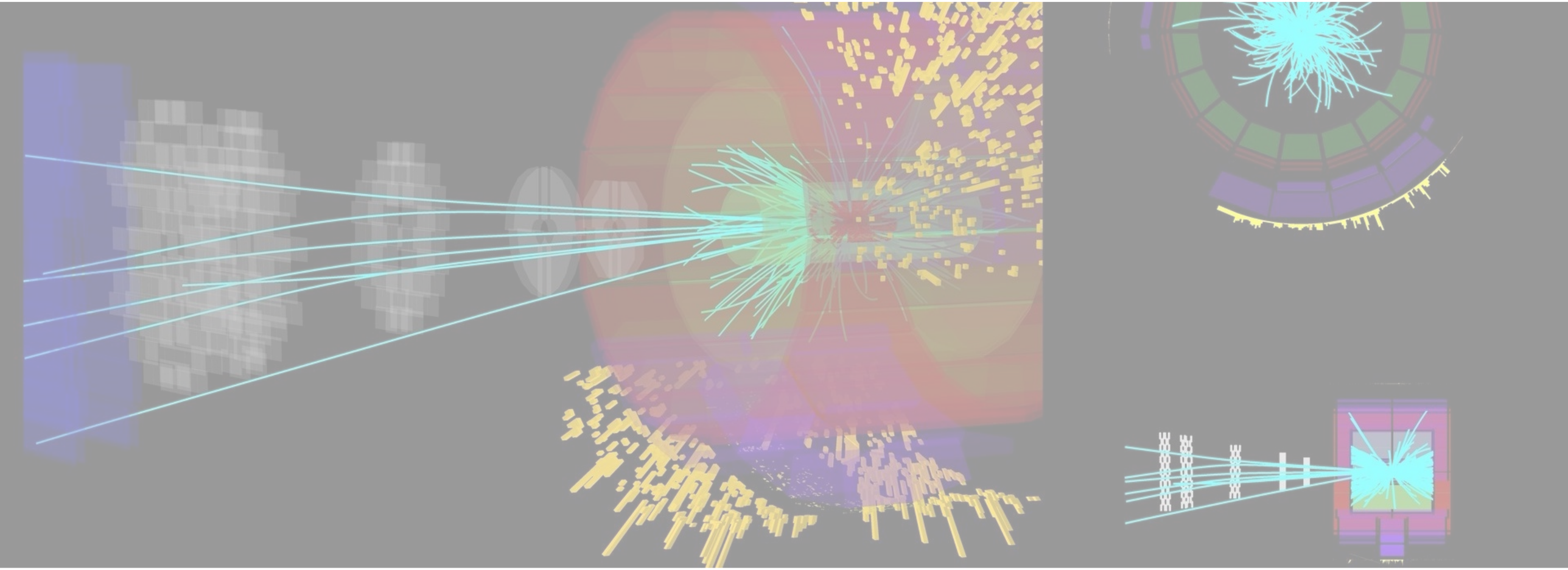
Prospect for Run 3

- Larger data sample → will benefit for both mid & forward y
- New muon forward silicon tracker (MFT) will allow prompt vs non-prompt separation for both J/ψ , $\psi(2S)$
- First $\psi(2S)$ azimuthal anisotropy (v_2) down to low-p_{T}, azimuthal distributions & polarisation of photoproducted J/ψ
- Excellent momentum resolution will allow p_{T}-differential charmonium σ_{coh} measurements (with the study of full nucleus vs spectators for the coherence condition)
- Study of possible interaction of photoproducted $\mathrm{J}/\psi \leftrightarrow$ QGP
- Photoproduced J/ψ could be a completely new probe of the charmonium dissociation in the QGP



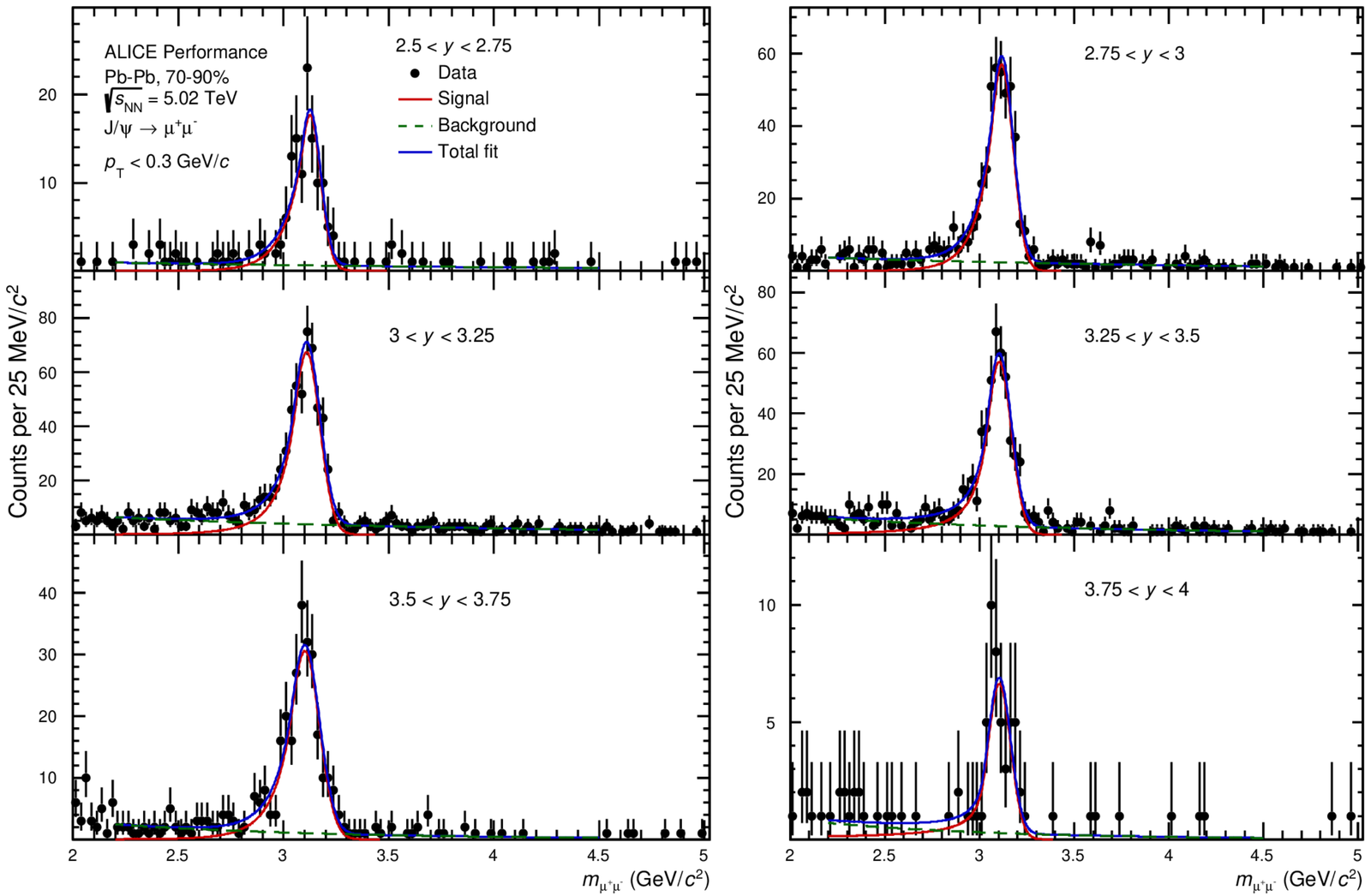
First Pb-Pb collisions recorded in Run 3

Thank you for your attention!



Run 3 started: new measurements are coming soon

Ongoing y-differential J/ψ photoproducted measurement in Pb-Pb



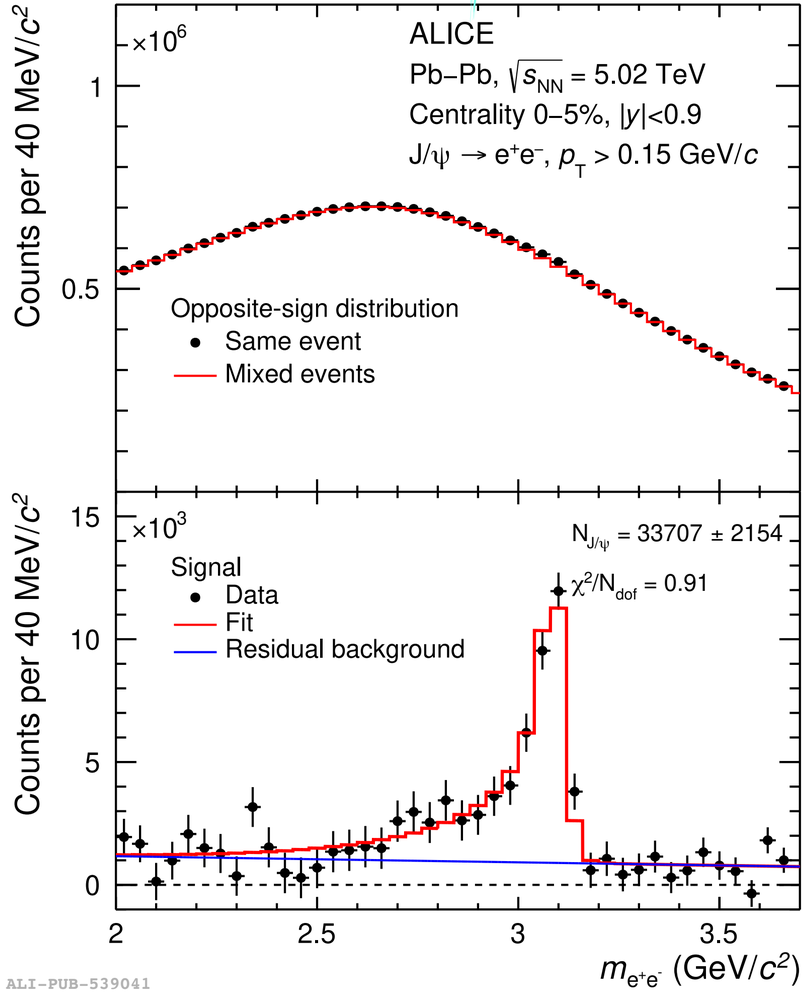
ALI-PERF-538924

NEW RESULT SOON:
ONGOING ANALYSIS

- Large dimuon candidates collected at forward rapidity allow to perform y-differential extraction
- Important to add more constrains on $\mathrm{d}^2\sigma/\mathrm{d}p_\mathrm{T}\mathrm{d}y$

e^+ e^-

$J/\psi \rightarrow ee$

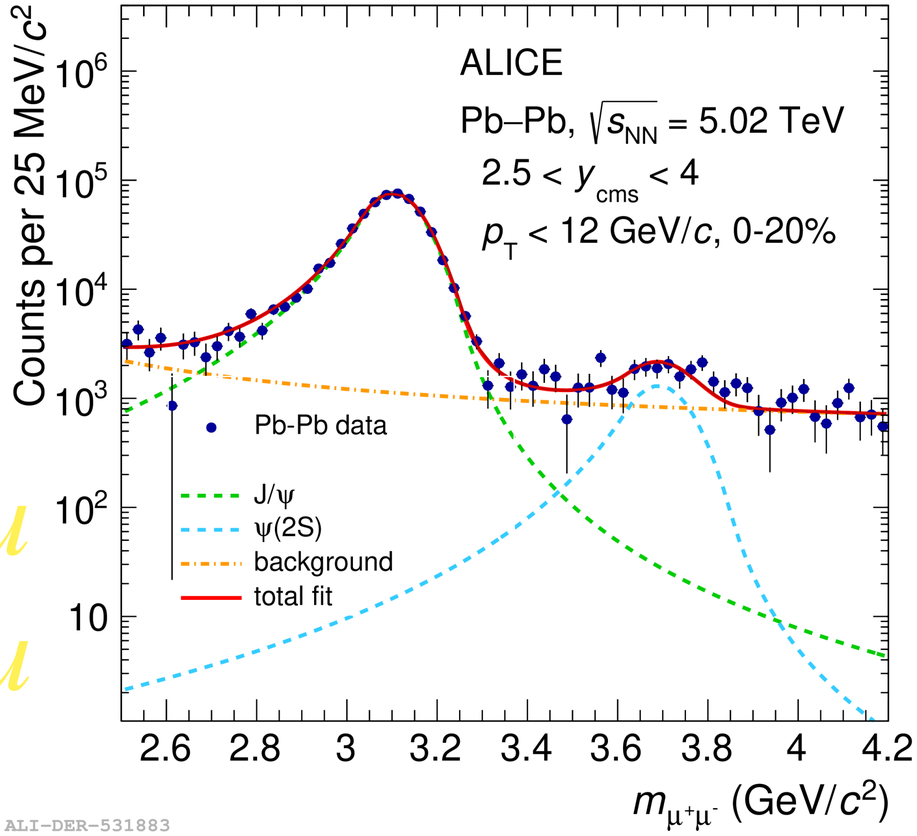


μ^+

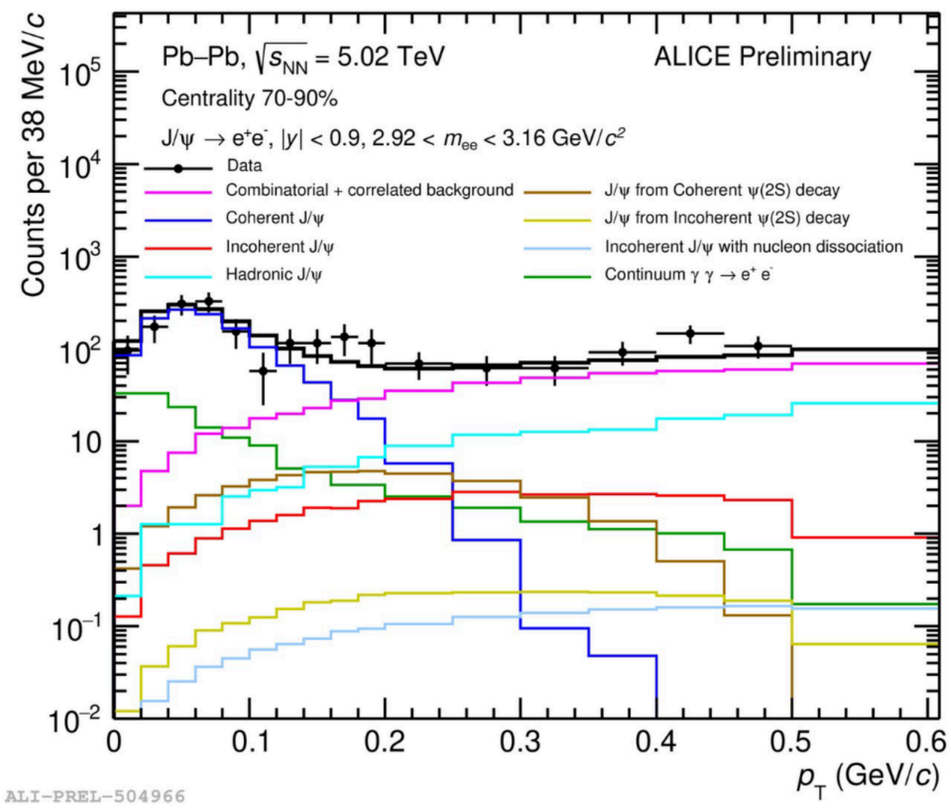
μ^-

$J/\psi \rightarrow \mu\mu$

$\psi(2S) \rightarrow \mu\mu$

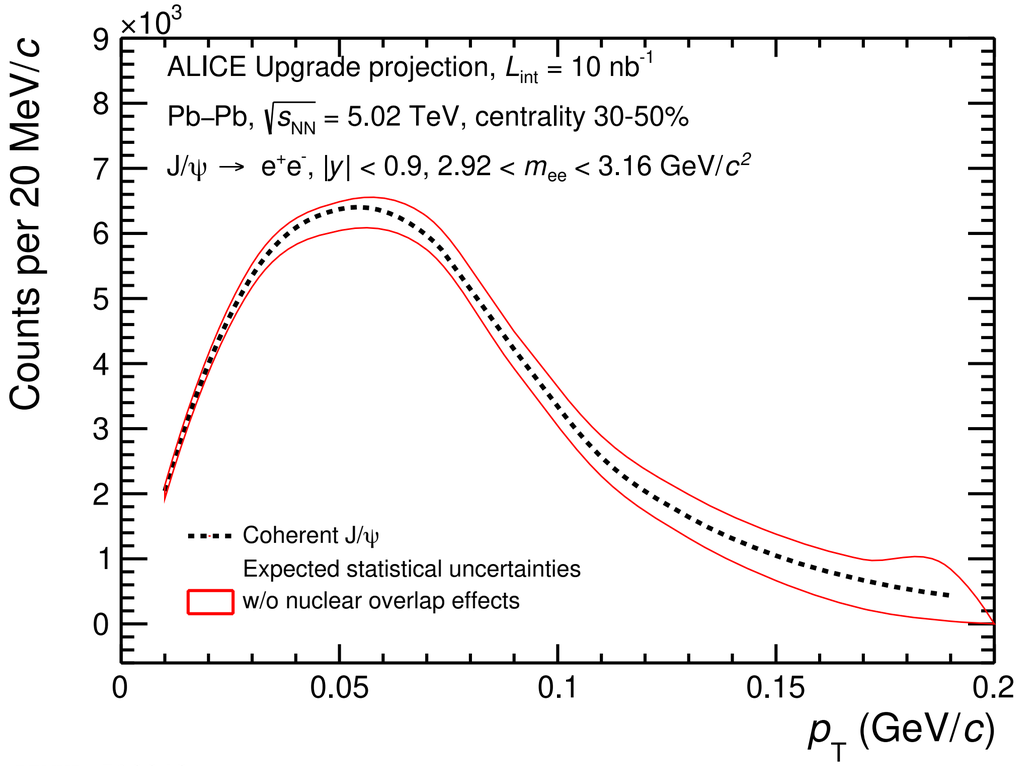


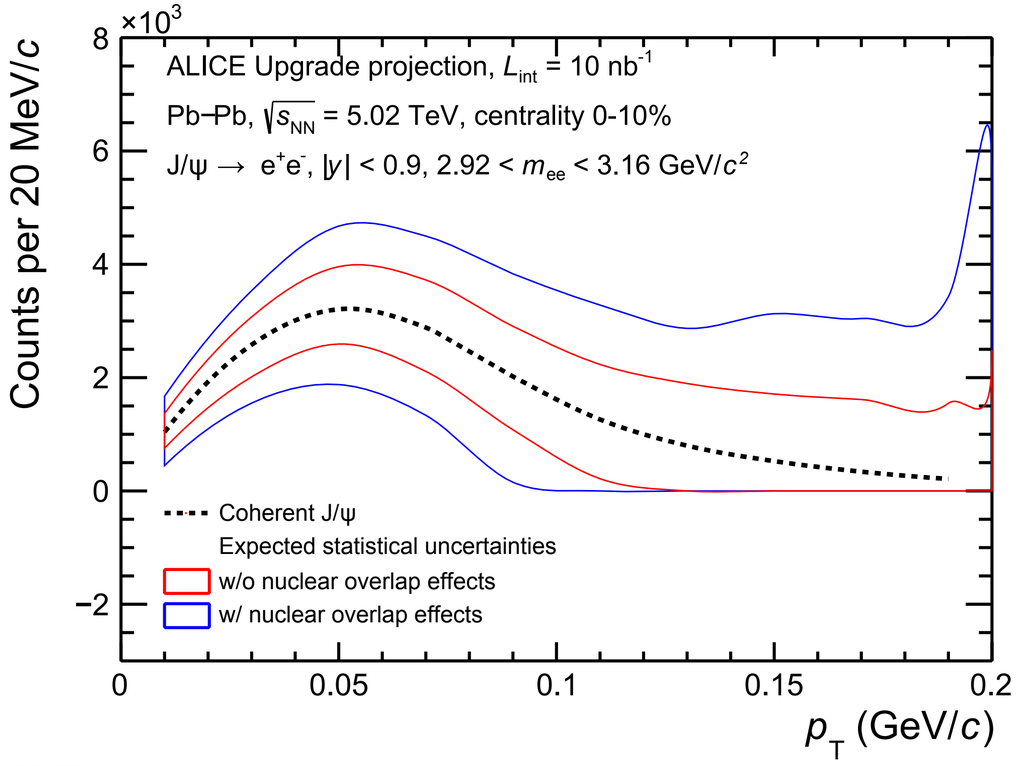
Extraction of photoproducted J/ψ



- Coherent production extracted using a template fit:
  - Photoproduction components, hadronic J/ψ production, combinatorial and correlated background
- Photoproduction templates based on STARLIGHT simulations:
  - coherent J/psi, incoherent J/ψ (and with nucleon dissociation), feed-down from coh. and incoh. ψ (2S), gamma-gamma continuum

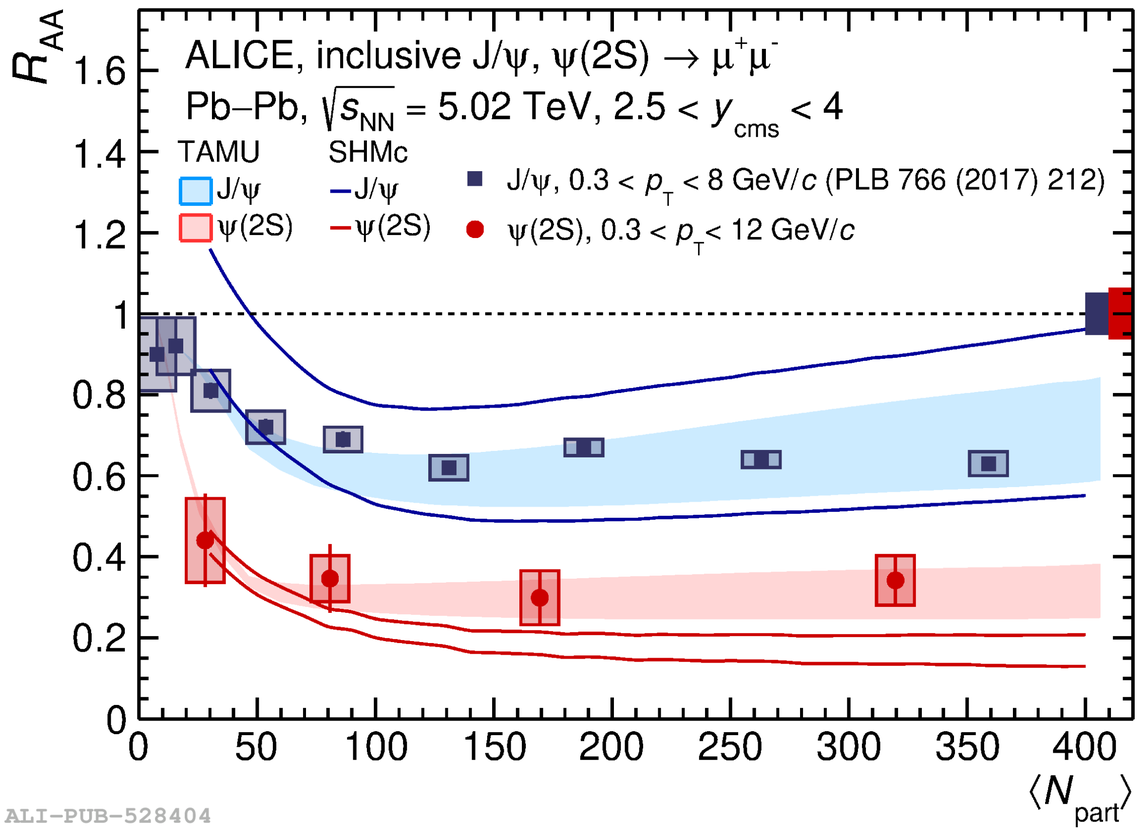
Projection of J/ψ photoproduction in Pb-Pb at midrapidity

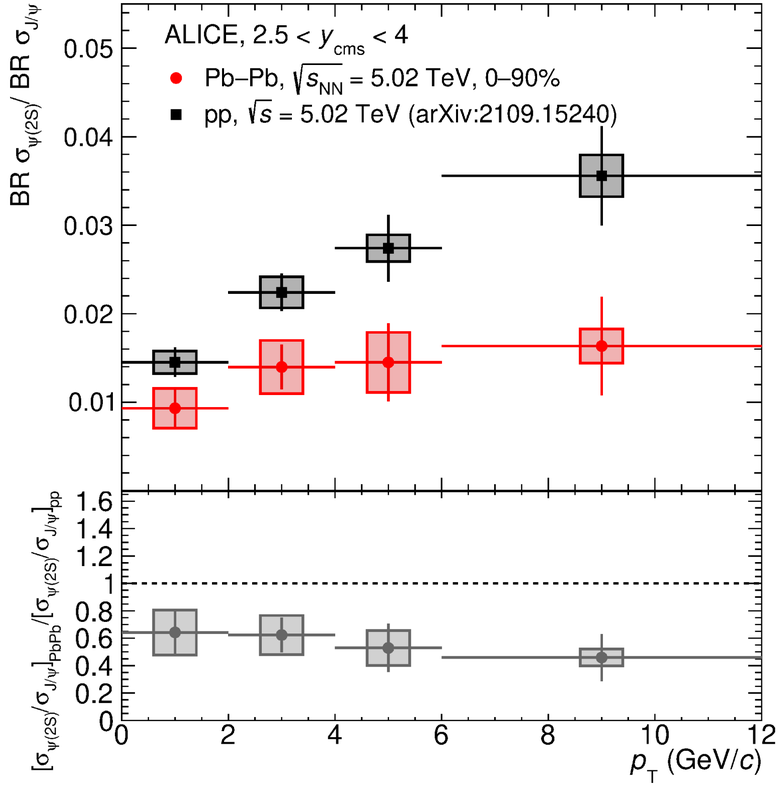




- J/ψ photoproduction in peripheral Pb-Pb will be much precise with $L_{\mathrm{int}} \sim 10\ \mathrm{nb}^{-1}$
- Central collisions for 0-10% will be available to constrain more theoretical models

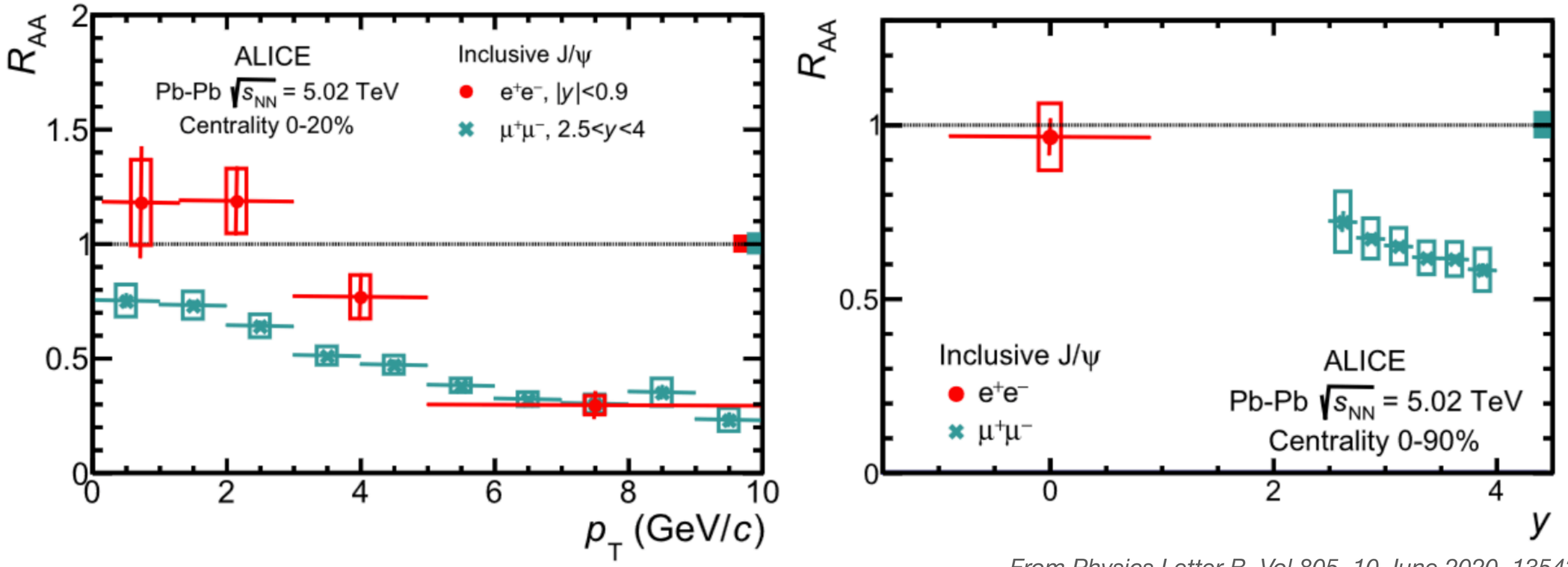
J/ψ and $\psi(2S)$ production in Pb-Pb collisions





- Double ratio values indicate the relative suppression of the $\psi(2S)$ w.r.t. J/ψ which is decreasing slightly with p_T up to ~ 0.5

J/ψ production over p_T and rapidities



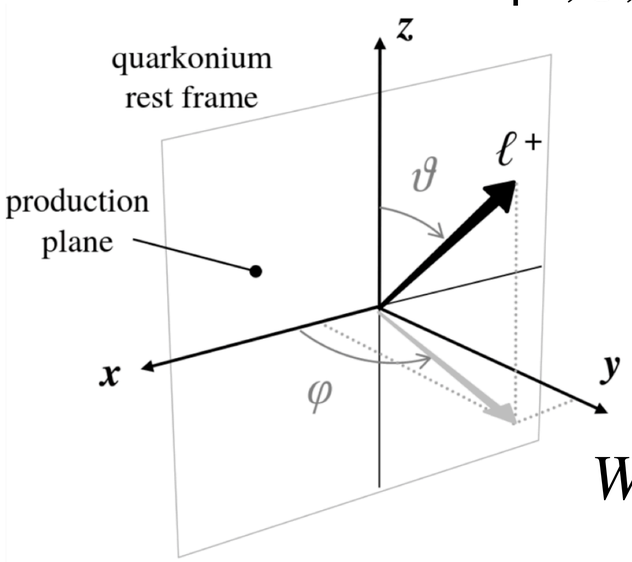
From Physics Letter B, Vol 805, 10 June 2020, 135434

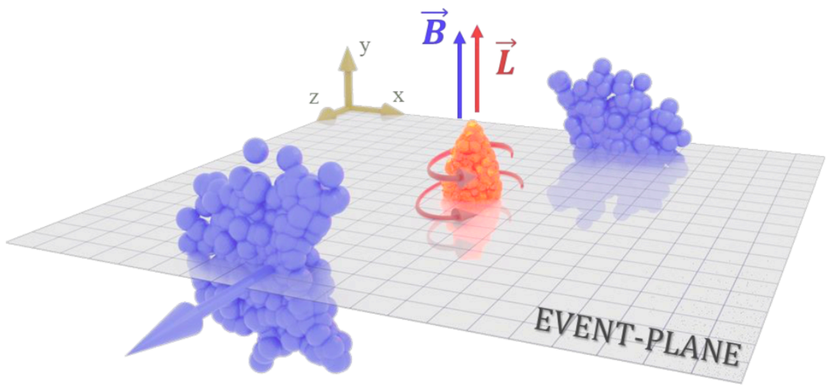
- Larger recombination effects are expected for mid-rapidity compared to the forward rapidity region

J/ψ polarisation in Pb-Pb collisions

- Related to **spin alignment of a particle w.r.t a given axis**
- For a vector meson ($\mathbf{v}$), the total angular momentum ($\mathbf{J}, \mathbf{J}_z$) is:

$$|v; \mathbf{J}, \mathbf{J}_z> = b_{+1}|1,+1> + b_0|1,0> + b_{-1}|1,-1>$$





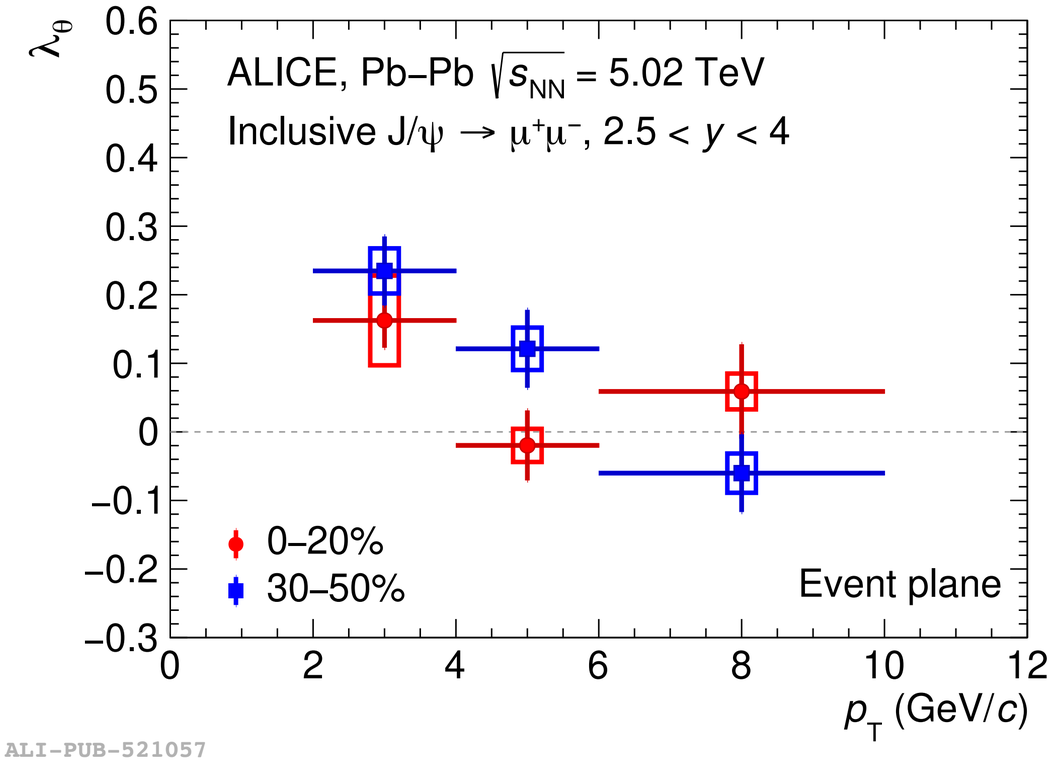
$$W(\cos\theta, \varphi) \propto \frac{1}{3+\lambda_\theta} \cdot (1 + \lambda_\theta \cos^2\theta + \lambda_\varphi \sin^2\theta \cos 2\varphi + \lambda_{\theta\varphi} \sin 2\theta \cos 2\varphi)$$

$(\lambda_\theta, \lambda_\varphi, \lambda_{\theta\varphi}) = (+1,0,0)$ → Pure longitudinal

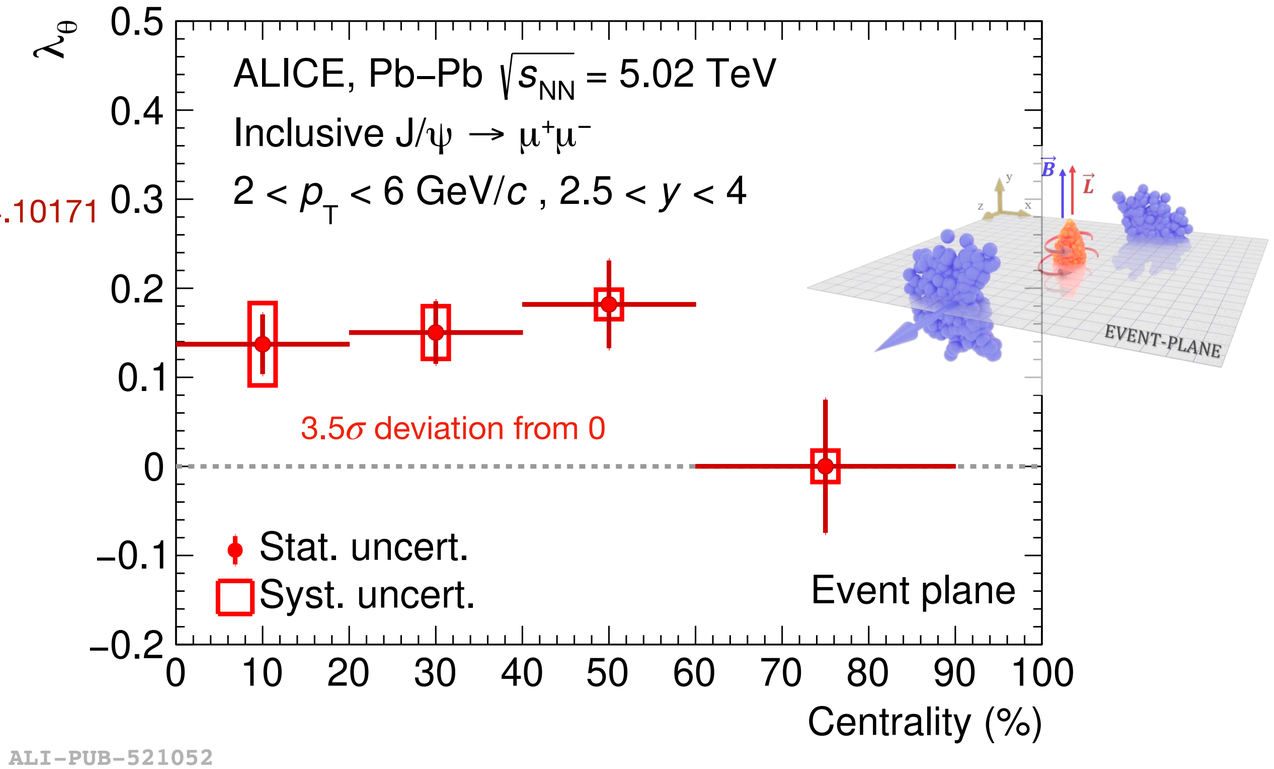
$(\lambda_\theta, \lambda_\varphi, \lambda_{\theta\varphi}) = (0,0,0)$ No polarisation

$(\lambda_\theta, \lambda_\varphi, \lambda_{\theta\varphi}) = (-1,0,0)$ → Pure transverse

J/ψ polarisation vs event plane in Pb-Pb collisions

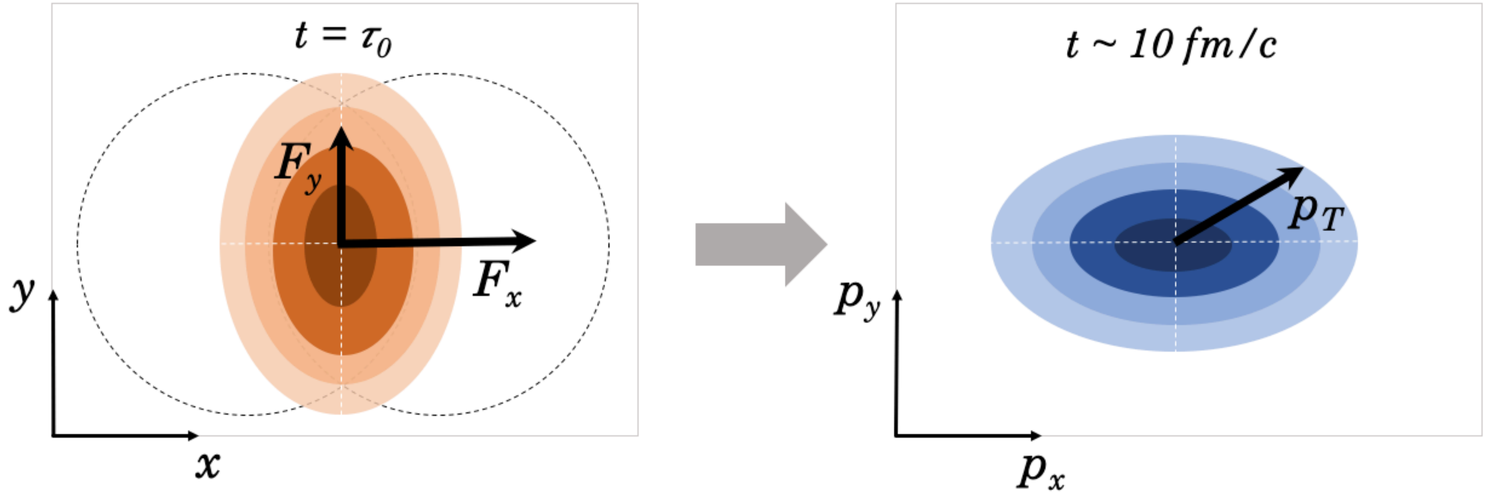


arXiv:2204.10171



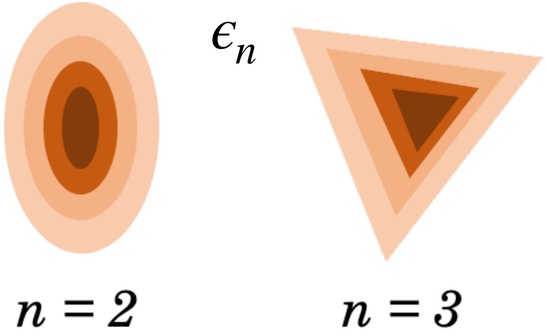
- Vanishing polarisation at larger momenta
- **First evidence** of J/ψ polarisation w.r.t. EP at low p_T (possibly larger in semi-central events)
- Sensitivity to **vorticity and B field**?

v_n coefficients in Pb-Pb collisions



- Related to **initial geometry** of the overlap region and **high pressure gradients**
- Spatial anisotropy is transferred into a **momentum space anisotropy**

$$\frac{dN}{d\varphi} \propto 1 + 2\sum_{n=1} v_n \cos n(\varphi - \Psi_n)$$

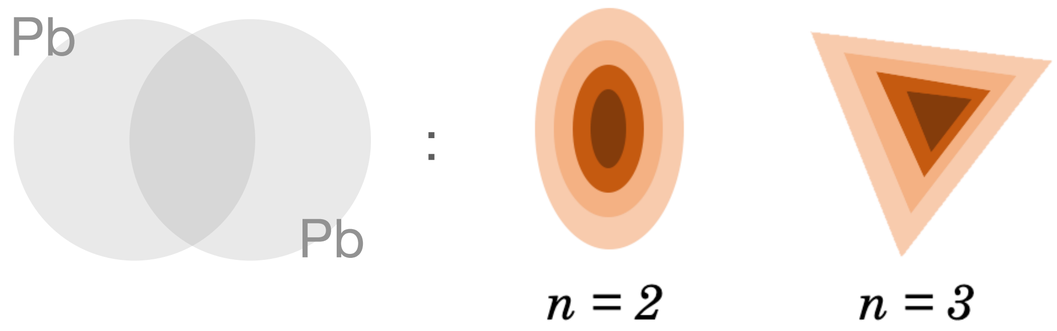


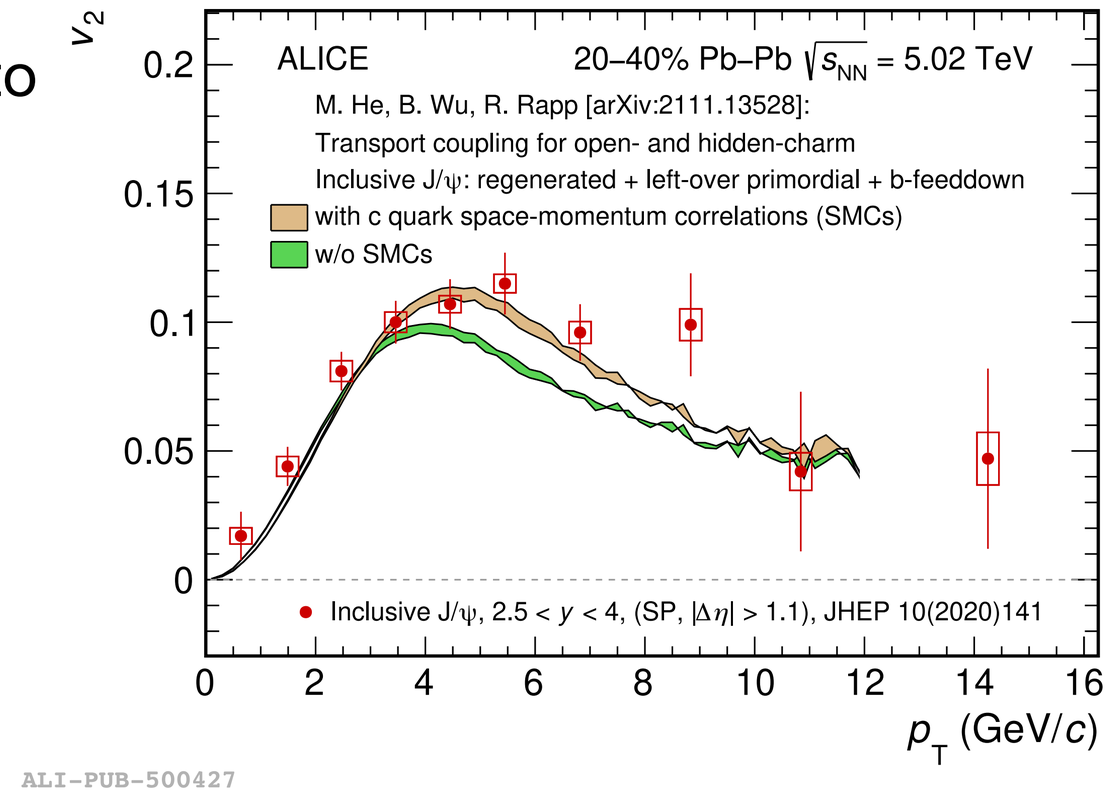
$$v_n = < \cos n(\varphi - \Psi_n) >$$

Elliptic flow v_2

- Initial spatial anisotropy is converted into a **momentum space anisotropy**

$$\frac{\mathrm{d}N}{\mathrm{d}\varphi} \propto 1 + 2\sum_{n=1} v_n \cos n(\varphi - \Psi_n)$$



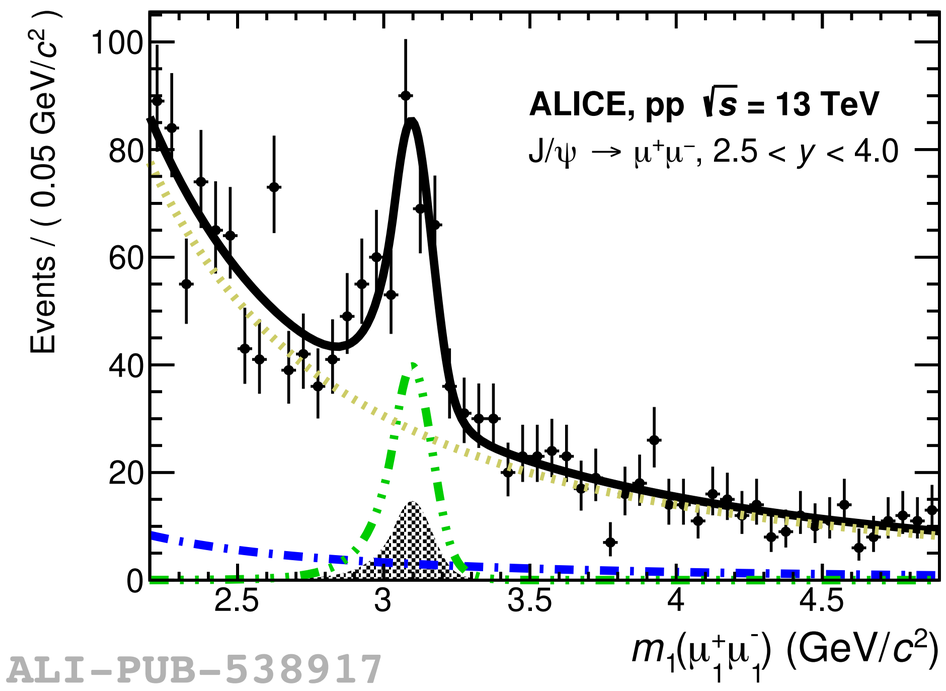


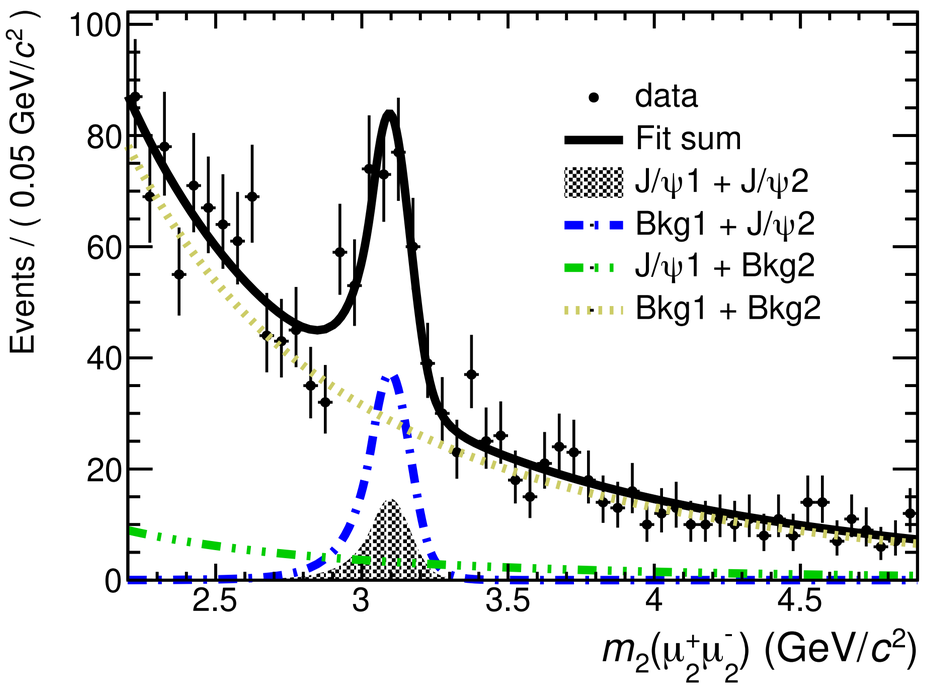
- Low p_T (< 5 GeV/c): transport model implementing **regeneration** can describe measured J/ψ v_2, the latter inherited from collective flow of c quarks during recombination

- High p_T v_2: path-length dependence mechanism + c quark space-momentum correlations

J/ψ pair production in pp collisions

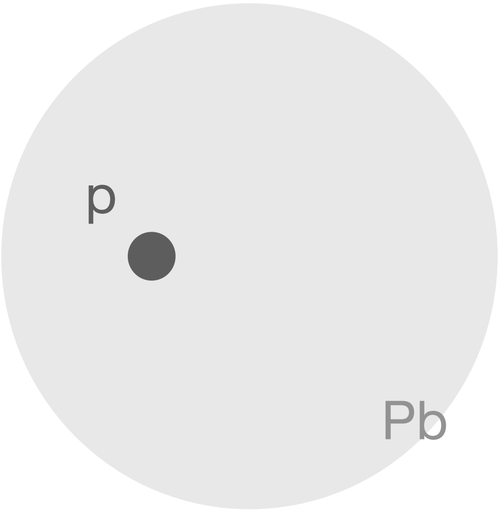
arXiv:2303.13431

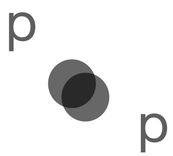




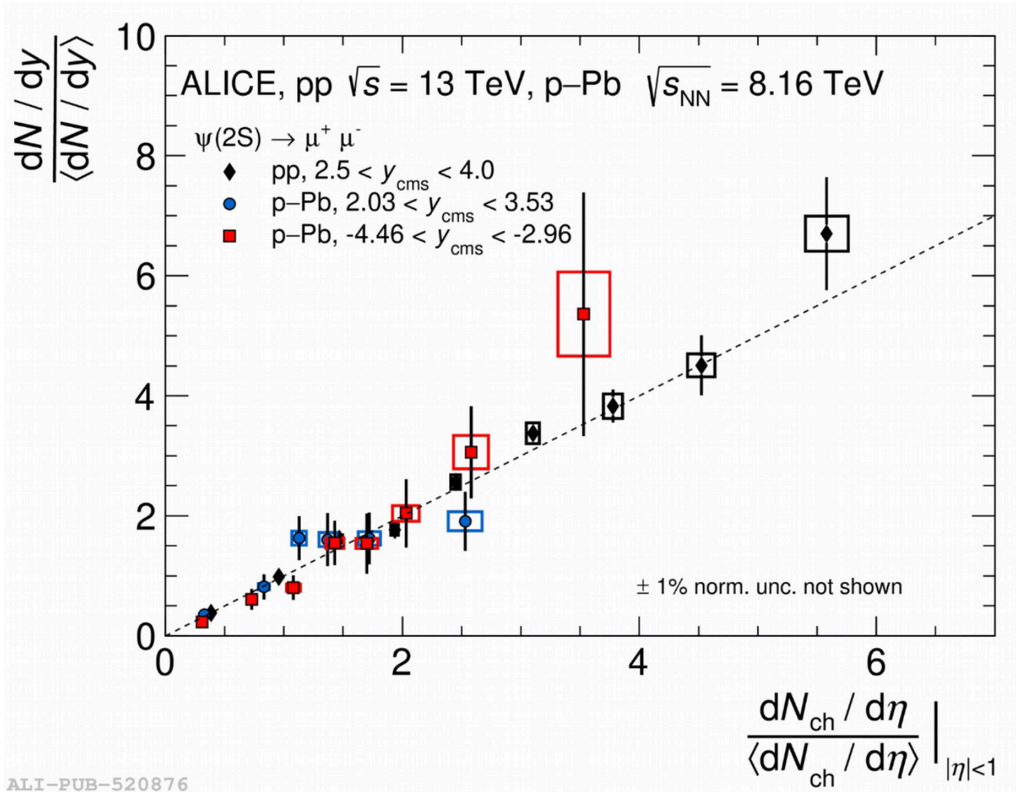
- Constrains on J/ψ production (NRQCD) and double parton scattering
- Despite different acceptance and inclusive or prompt: good agreement w LHCb result

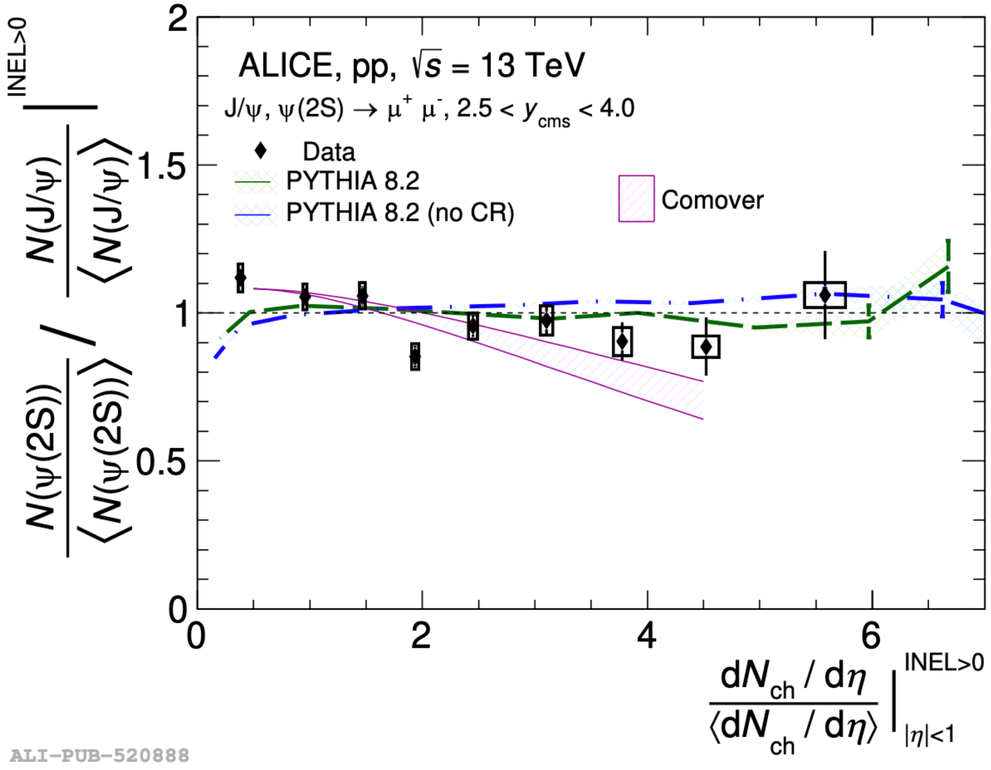
Going towards small collision systems





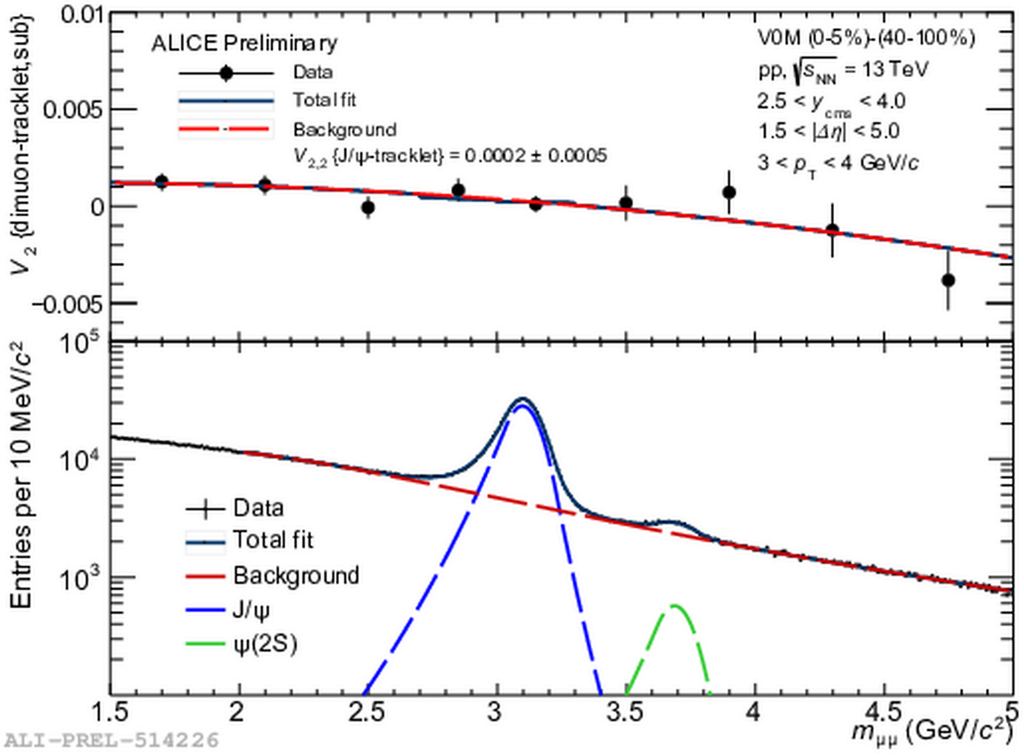
$\psi(2S)$ production in pp and p-Pb collisions

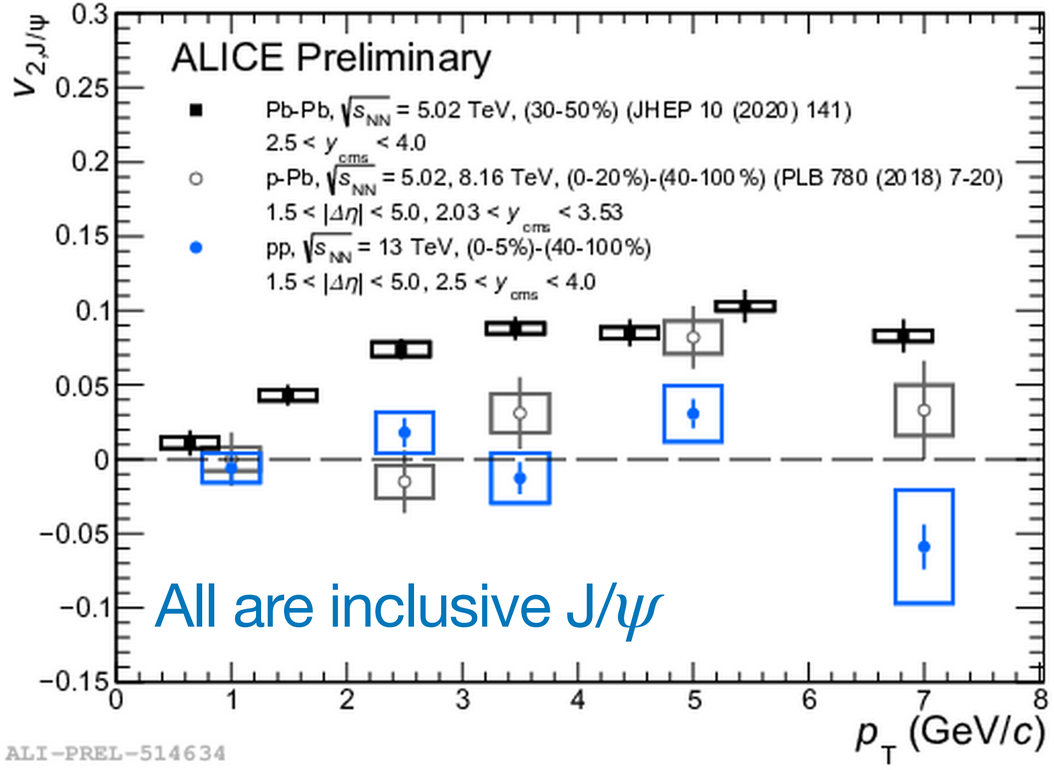




- Linear increase of $\psi(2S)$ normalized yield vs. multiplicity while $\psi(2S)/\mathrm{J}/\psi$ is flat
- Agreement with models at low p_{T}
- pp and p-Pb data are compatible within the uncertainties

$v_2^{J/\psi}$ measurement in pp collisions



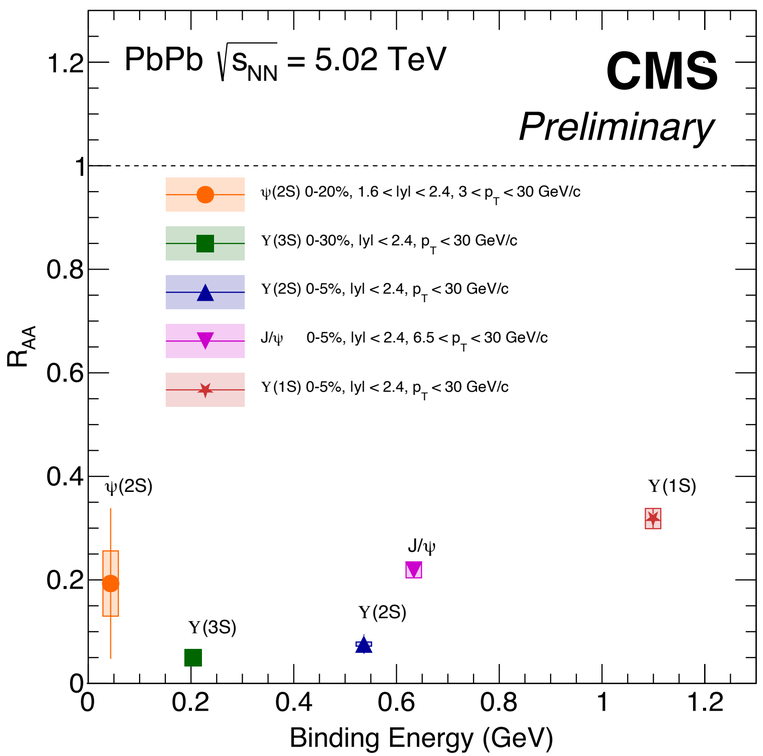


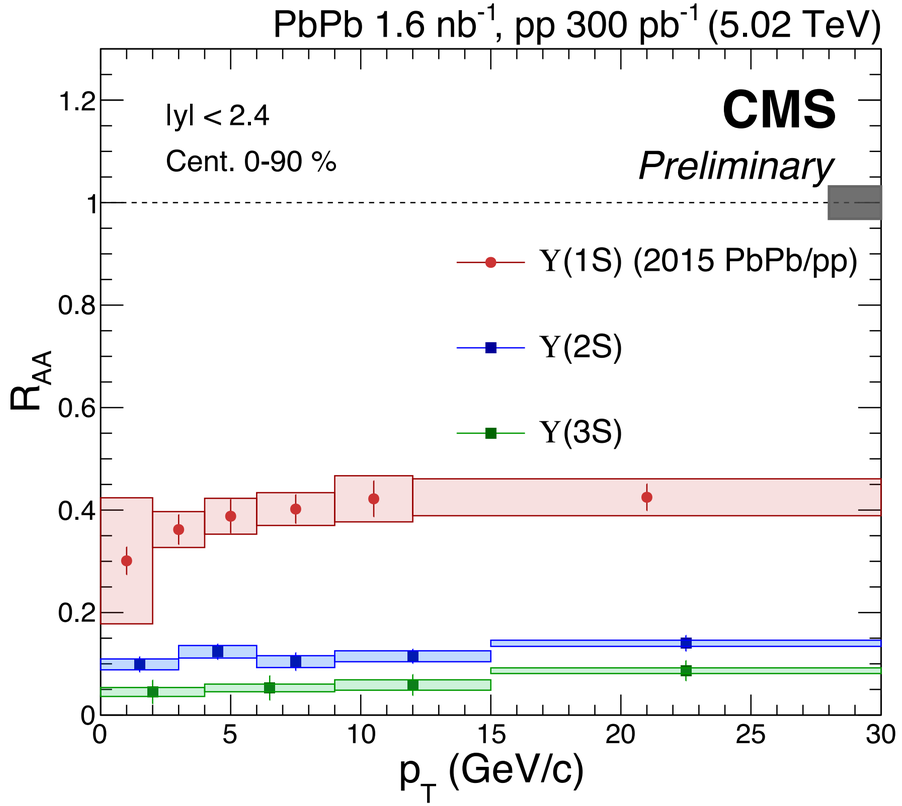
PbPb
pPb
pp

- Collective effects observed for light flavours… open question for heavy flavours
- No significant p_T dependence and $v_2^{J/\psi}$ in pp **compatible with 0** ($v_2^{pp} < v_2^{pPb} < v_2^{PbPb}$)

Other LHC experiment results

Integrated and p_{T}-differential R_{AA}

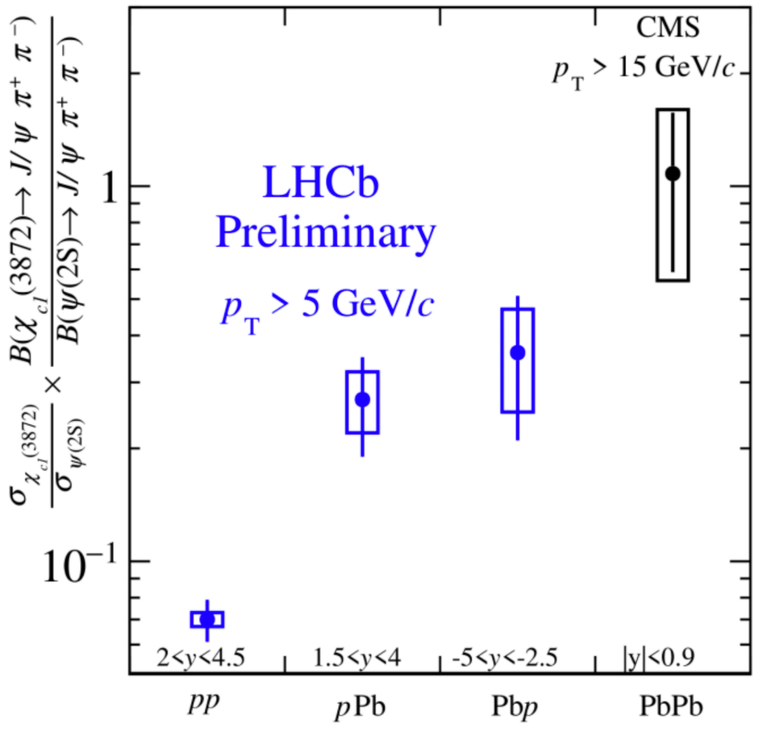


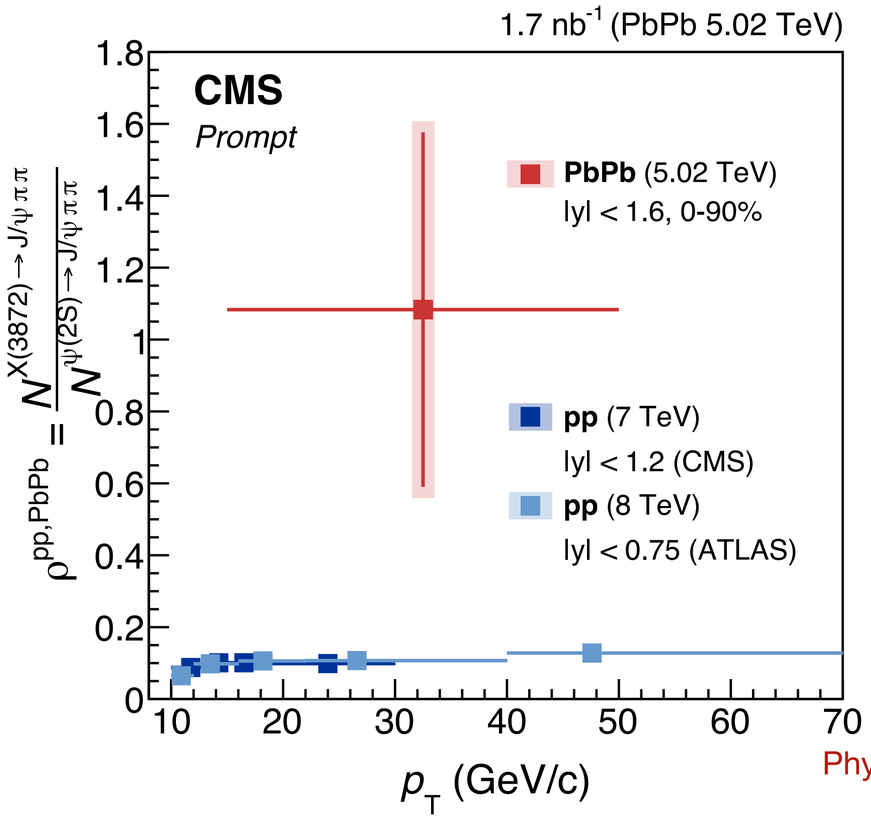


- Sequential suppression for conventional charmonia and bottomonia states
- Larger R_{AA} when the binding energy is increasing

X(3872) measurement in Pb-Pb collisions

[LHCb-CONF-2022-001]





$u\bar{c}\bar{u}c$

Tetraquark

or

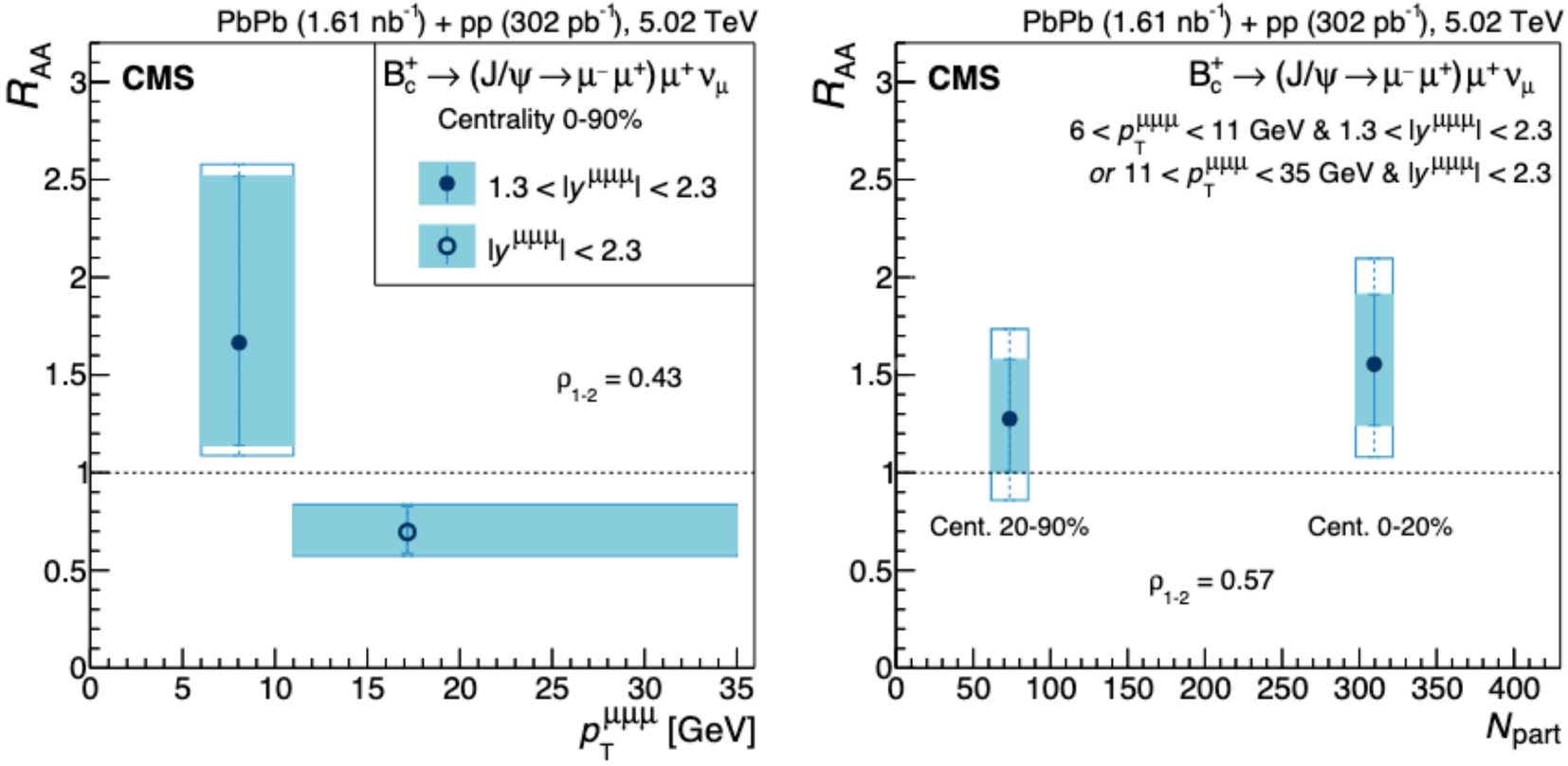
hadron molecule

?

Phys. Rev. Lett. 128, 032001

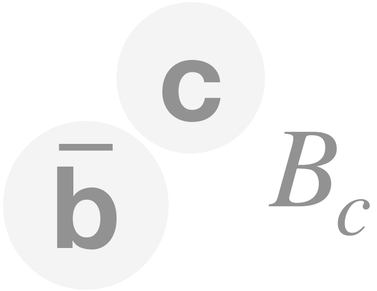
- First evidence of X(3872) in Pb-Pb is reported: 4.2σ standard deviation
- Prompt X(3872) to $\psi(2S)$ yield ratio: **unique experimental** input for theory
- Indication for **medium-induced coalescence**

B_c measurement in Pb-Pb collisions

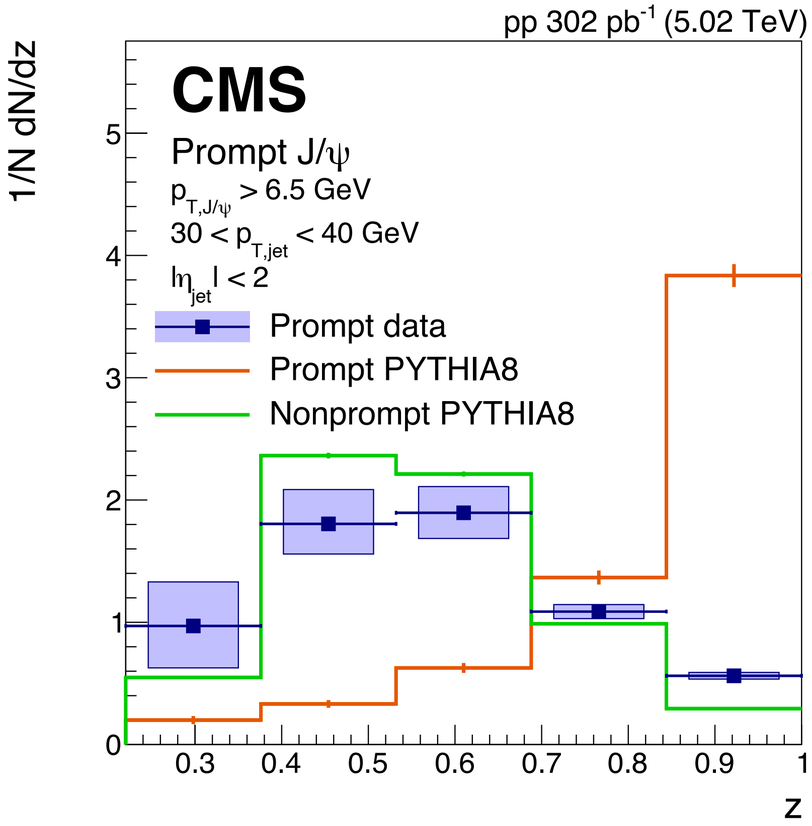


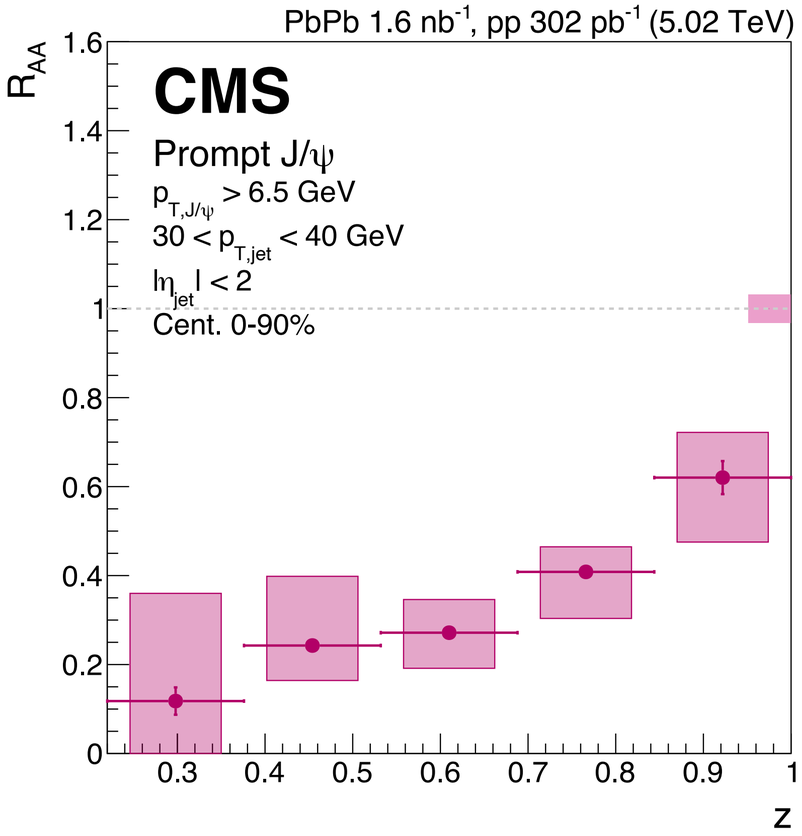
arXiv:2201.02659

- Evidence of very large R_{AA} in Pb-Pb is measured w.r.t. quarkonia
- Further indication for **coalescence** mechanism



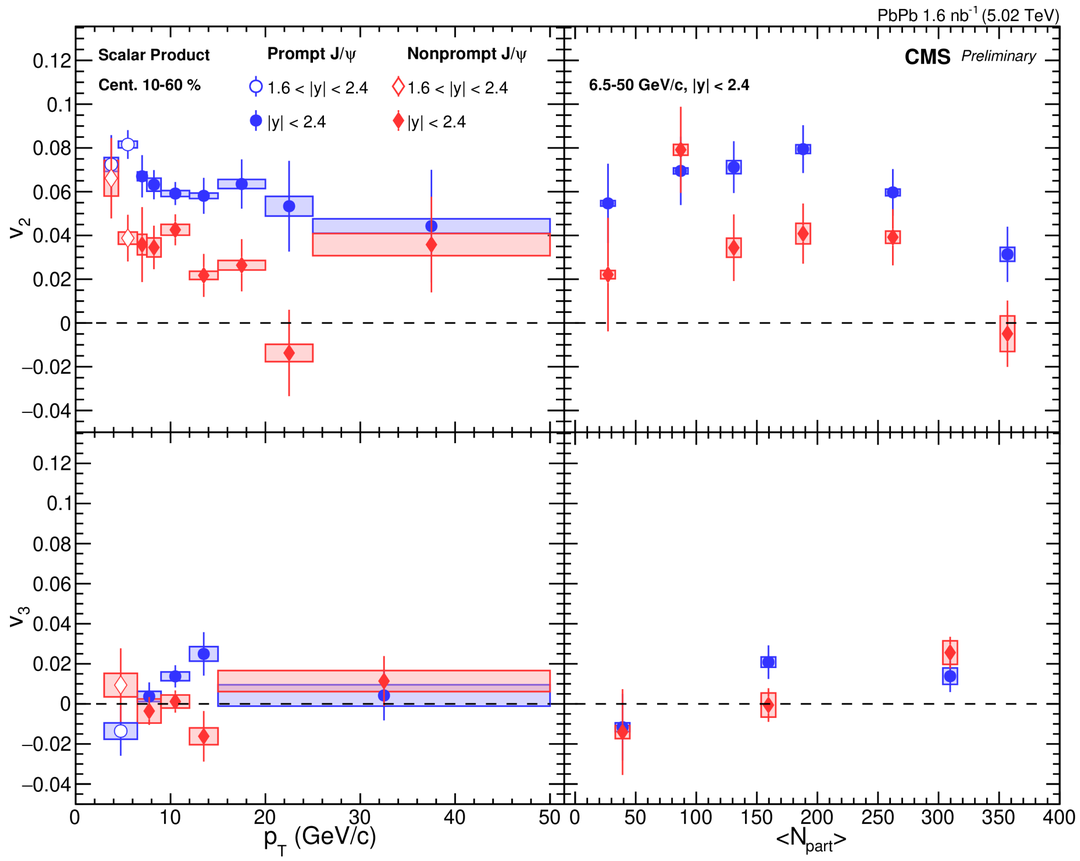
Fragmentation of jets with prompt J/ψ in Pb-Pb and pp

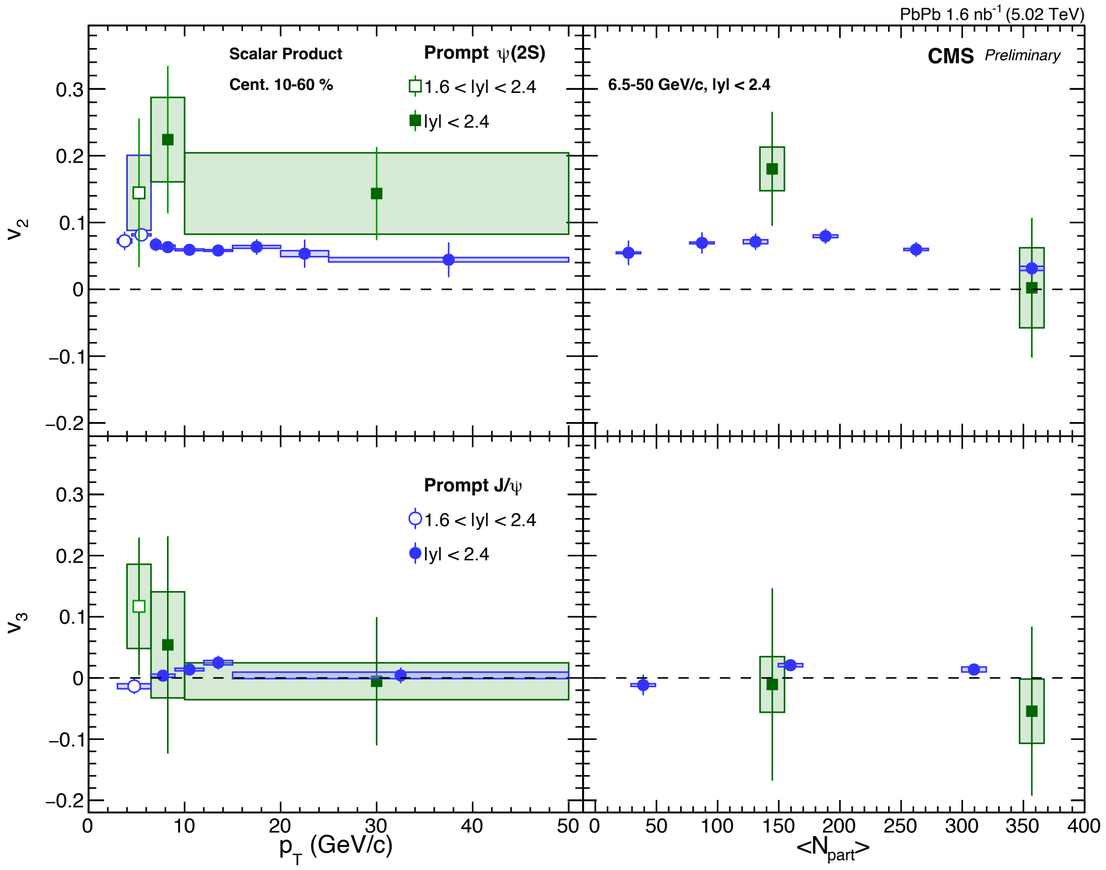




- Hint of a z-dependence of the J/ψ suppression ($z = p_{T,J/\psi}/p_{T,jet}$)
- Indication that the J/ψ - medium interaction depends on the fragmentation

J/ψ and prompt $\psi(2S)$ v_n in Pb-Pb collisions





- Larger v_2 is observed for prompt J/ψ w.r.t. non-prompt while all ~0 for v_3
- Hierarchy is observed: $v_2^{b\to J/\psi} < v_2^{J/\psi} < v_2^{\psi(2S)}$ however not clear w.r.t. centrality